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Safety in a nuclear facility means a design accorded to the processes and materials used and to the resulting risks for the workers, the public and the environment. This requires having the necessary scientific and technical knowledge to assess risks during normal operation, incidents and accident situations. This knowledge is essential for operators when designing facilities (for example relating to containment and ventilation), defining operating conditions (to control process parameters, for example), adopting protective measures for workers (to ensure radiation protection), and preparing safety and radiation protection justifications to be included in the relevant safety documents.

IRSN, in order to assess nuclear safety and radiation protection during construction, operation, modifications, safety reviews and decommissioning, must also have the necessary knowledge to form its own opinion on the measures taken by operators to control risks. This is achieved by conducting studies and research, generally on specific subjects that are essential to understanding risk, investigated when necessary with various partners through joint funding. Research contributes insight into the phenomena involved and provides material to sustain IRSN’s expertise, serving to support the Institute’s opinion on measures taken by nuclear operators.

The following articles provide examples of the issues dealt with by IRSN in the field of safety for a wide range of facilities including industrial plants, nuclear reactors and radioactive waste repositories.

One of the significant fields targeted by these studies concerns assessing the risk of radioactive substances being released inside buildings or to the environment, either during normal operation or in an accident situation. The first article in this chapter concerns monitoring atmospheric contamination, which is important for detecting a possible loss of radioactive containment. It describes IRSN’s efforts to evaluate the performance of continuous air monitors under real operating conditions. The second article concerns the behavior of filtration equipment before it releases air from ventilated rooms in the event of fire. This equipment is designed to limit environmental release, and its performance in accident situations, such as fire, must be assessed carefully. The article discusses experiments to assess HEPA filter clogging by aerosols produced during fire, since clogging is one of the phenomena that can lead to the loss of filter integrity.

Another broad field of study involves probabilistic safety assessments (PSAs) carried out for pressurized water reactors (PWRs) to identify and quantify accident sequences leading to core melt. PSAs involve a series of technical analyses conducted to assess risks in terms of frequency and consequences of postulated initiating events. On this basis, they help define and prioritize actions to be taken to reach or maintain a satisfactory safety level, in addition to deterministic methods, which are given precedence. PSAs have become an indispensable tool for safety assessments. They are used regularly in IRSN technical opinions, particularly during safety reviews.
on existing reactors or in designing new reactors (EPR). The three articles on this topic concern development work by IRSN concerning PSAs relating to fire risks for 900 and 1,300 MW(e) reactors and Level 1 PSA for the Flamanville 3 EPR.

Finally, a more specific field of research concerns the safety of radioactive waste repositories in deep geological formations, which requires assessing changes in repository system over time. The last article of this chapter concerns post-closure hydromechanical behavior of an underground structure, a subject particularly relevant for assessing long-term repository safety.
PERFORMANCE ASSESSMENT of continuous air monitors under real operating conditions

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In the nuclear industry, workers may be exposed to artificial radioactive aerosols. These aerosols are generally composed of particles with a diameter ranging between 0.1 µm and 10 µm [Perrin, 1985]. In major accidents, observations have shown that the size of particles released to the environment falls within this range [Budyka and Ogorodnikov, 2005]. To protect workers in nuclear facilities or assess the consequences of contamination released as aerosols in the environment, monitors that continuously measure radioactivity in the air are used. The main function of the monitor is to provide real-time measurement of activity concentration in the facility and in the air discharge stack in order to activate an alarm when necessary, or ensure that releases are within authorized limits.

Measurement of aerosol activity concentration can be affected by a number of factors specific to the aerosols (size distribution, radionuclide type, presence of naturally-occurring radioactive aerosols, etc.) and the instrument (detector type, data processing, air flow system, sampling filter, etc.). Due to the complexity of the measuring instrument, it is impossible to determine its response using a model, thereby making calibration necessary.

The tests to be performed to calibrate monitors are described in several International Electrotechnical Commission (IEC) standards. There are two types of tests: "static" tests, carried out using standard solid radioactive sources, and "dynamic" tests, using standard radioactive aerosols. Dynamic tests determine instrument performance under actual operating conditions in the presence of different combinations of artificial and natural (radon decay) aerosols.

These tests are necessary to receive certification from IRSN’s technical center responsible for approving radiological protection instrumentation (CTHIR) for manufacturers or industrial users who request it.

The first part of this article presents the general operating principles of continuous air monitors (CAMs) and inherent measurement difficulties, as well as the main standard tests. The second section describes the experimental facility at the Aerosol Physics and Metrology Laboratory (LPMA) at IRSN, which carries out dynamic tests using standard radioactive aerosols. Test results from two types of monitors available on the market are presented in the third section.
Operating principles and characteristics of continuous air monitors

Figure 1 schematically represents the principal components of a CAM, i.e., a sampling system (air flow duct and particulate filter), a nuclear radiation ($\alpha$, $\beta$, or $\gamma$) detector and a module for measuring and checking the sampling flow rate. The sampling system must take representative samples of granulometry, chemical composition and aerosol activity concentration [McFarland et al., 1990]. It must also ensure aerosol collection on a retention medium, usually a fiber filter, placed opposite a radiation detector.

Figure 1a shows a diagram representing an environmental monitor in which sampling is not channeled and Figure 1b the case of a monitor with a sampling bulb. The use of a sampling bulb optimizes aerosol collection on the filter and is practical for taking measurement samples in ducts.

The photographs in Figure 2 show the MONICA sampling head with bulb designed at IRSN [Charuau, 1985]. The bulb is a complex object, since it is designed to sample particles while leaving a minimum deposit in the sampling system and forming a homogeneous particle distribution on the filter surface. On certain devices, the shape of the bulb removes the component resulting from naturally occurring radioactivity (radon decay products).

The choice of collection filter is crucial for obtaining an accurate measurement of collected activity. In the nuclear industry, several types of filters are used. For taking samples for off-line radiation measurements, filters manufactured by Bernard Dumas are the most frequently used, such as the B132 pure cellulose filter, the C357 fiberglass filter, or the C569 mixed fiberglass and cellulose filter. For CAMs, most manufacturers currently tend to use Millipore's teflon FSLW filter or the fiberglass GF/A filter manufactured by Whatman [Cohen et al., 2001]. The diversity
In general, instruments measure natural activity concentration using complex algorithms that require either “teaching” the monitor about its environment, or taking measurements over a long period to establish a dynamic measurement of radon decay products. The discussion of results at the end of this article demonstrates the need to compensate naturally-occurring radioactivity. Monitors also have a detector for measuring the ambient $\gamma$ dose rate.

A monitor can therefore be viewed as a complex device that must be tested using well-defined methods before it is used in a facility. The IEC has developed test standards for this purpose: the IEC 60761 series, Ed. 2 (2002), which covers all dynamic tests under actual operating conditions; IEC 61172 Ed. 1 (1997) for static tests, and IEC 61578 Ed. 2 (1997), which deals with radon. All of these tests combined give a complete view of monitor performance. The most important tests proposed are:

- reference response for standard radioactive aerosols;
- response with a standard test source;
- response for a mixture of artificial aerosols and radon decay products;
- radon compensation study;
- monitor collection efficiency for several particle diameters;
- monitor linearity as a function of activity concentration;
- detection efficiency according to radionuclide;
- correlated detection efficiency for $\alpha$ and $\beta$ particles;
- statistical fluctuations;
- stability of indications over time;
- increase in background noise for an ambient dose rate of 10 $\mu$Gy/h;
- preheating time;
- operation at temperatures up to 35°C and a relative humidity of 90%;
- sampling rate as a function of head loss;
- alarm test.

To carry out CAM tests according to the requirements in these standards, the ICARE test bench (a calibration facility based on standard radioactive aerosols) is used [Ruzer et al., 2005]. In addition to standard tests, this experimental facility can carry out operating tests on all monitor types under actual operating conditions.

**Description of the ICARE monitor test facility**

The ICARE facility was designed in the mid-1980’s [Ammerich, 1989] to test continuous air monitors under representative operating conditions to determine the actual monitor response and the effectiveness of radon compensation [Grivaud et al., 1998].
The ICARE facility is composed of a 120 mm diameter air duct in which filtered air circulates at a controlled flow rate of approximately 56 m$^3$/h. The different radioactive substances that can be measured are artificial and natural aerosols, noble gases, tritium, and iodine.

**Figure 3** shows a schematic diagram of the part of the facility that generates artificial and natural radioactive aerosols. **Figure 4** is a photograph showing an overall view of the facility. Upstream from the duct, there is an injection point for artificial aerosols produced by three generators contained in a glove box, and an injection point for generating natural aerosols. The section downstream from the duct is equipped with a sampling point for the reference measurement and three other points where the monitors to be tested are connected. Sampling is carried out using isokinetic probes designed to take samples at flow rates between 1 l/min and 1,000 l/min and take into account the flow rate circulating in the air duct.

The monitors designed for stack measurements using a sampling bulb (**Figure 1b**) are directly connected to the facility’s isokinetic probes using a leaktight Pneurop-type connection. In contrast, the environmental monitors without sampling heads (**Figure 1a**) are located in a glove box connected to the sampling probe. Measurements on particle deposits in the glove box are taken to ensure that deposits are negligible and that concentrations in the air duct and box are identical.

**Channel for generating artificial radioactive aerosols**

Aerosols are generated by pulverizing a solution using ultrasound. The liquid is pulverized to form a fog of microdroplets that are dried and entrained by a dry air flow. This type of ultrasound generator produces a significant concentration (several thousand particles per cm$^3$) that is stable over time and easily controlled by adjusting air flow. In addition, the particle size distribution is slightly polydisperse; it follows a lognormal distribution with a geometric standard deviation $\sigma_g$ between 1.3 and 1.5 [Bémer and Tierce, 1996].

The microdroplet diameter ($D_g$) depends on the resonance frequency of the ceramic pulverizer, superficial surface tension and liquid density. The volume-equivalent diameter ($D_{eq}$) of the dry
These relationships show that the ultrasound pulverization technique can be used to generate and control a wide range of aerodynamic diameters. The frequency specific to the generator determines droplet diameter. The ICARE test bench is equipped with three generators that use pure water to produce droplet diameters of $D_g \approx 25 \mu m$ for 80 kHz, $D_g \approx 5.4 \mu m$ for 800 kHz, and $D_g \approx 2.6 \mu m$ for 2,400 kHz. For a given droplet diameter, dry particle aerodynamic diameter can be varied through the salt concentration and type.

To generate radioactive aerosols, a solution containing the selected radioactive element, generally $^{239}$Pu or $^{137}$Cs, is added to a stock solution of cesium chloride (CsCl). Other radionuclides such as $^{90}$Sr or $^{60}$Co can also be used. Cesium chloride salt was selected because it is slightly hygroscopic and thus favors fast microdroplet evaporation. It is also an ideal compound for producing particles marked with $^{137}$Cs.

Americium-241 sources are placed downstream from the generators to produce a "pool" of bipolar ions that neutralize the aerosol, i.e., that impose a state of particle electric charge close to the Boltzmann equilibrium. This step minimizes electrostatic effects that can lead to particle deposit in the ducts. Moreover, self-charging phenomena for alpha and beta-emitting radioactive aerosols generated on the ICARE test bench are negligible, given the specific activity of the generated particles (about $10^{-4}$ Bq per particle) [Gensdarmes et al., 2001].

The ICARE test bench produces low-polydispersion radioactive aerosols with activity median aerodynamic diameters (Amad) between 0.1 µm and 10 µm. IEC 61578 recommends testing monitors using aerosols that have Amads ranging from 0.15 µm to 0.4 µm and 1.5 µm to 4 µm.

In general, tests are carried out for two aerosol size distributions that have Amads of approximately 0.4 µm and 4 µm. These values are selected because they are representative of radioactive aerosols that may be encountered in the environment or in plants. In addition, an aerodynamic diameter ratio equal to 10 entails a particle mass variation equal to 1,000 and a variation in their inertia (characterized by a relaxation time) equal to 100. This produces a wide variation in particle deposit phenomena, favorable to a modification in the instrument response as the aerosol median diameter changes.

Figure 4  Photograph of ICARE test bench.

Particles produced after microdroplet evaporation depends on salt concentration in the solution and microdroplet diameter. This is expressed as:

$$Dev = D_g \left( C_m \rho_m \right)^{0.1}$$

where $C_m$ represents salt mass concentration in the solution (kg/m³) and $\rho_m$ its density (kg/m³).

Aerodynamic diameter $D_a$ is expressed as a function of the volume-equivalent diameter by the relationship:

$$\rho_0 D_a^3 \cdot Cu(D_a) = D_g^3 \cdot C_m \left( \frac{C_m}{\rho_m} \right)^{0.1}$$

where $\rho_0$ represents the reference density ($\rho_0 = 1,000$ kg/m³) and $\chi$ the dynamic shape factor of the particle. The dynamic shape factor is a dimensionless parameter that is defined by the relationship between the drag force on the particle and the drag force on a sphere of the same volume as the particle; it is equal to 1 for spherical particles. $Cu(Dp)$ represents the Cunningham correction factor for a particle with a diameter of $D_p$.

Finally, for dry particles that are assumed spherical, aerodynamic diameter is expressed as a function of microdroplet diameter by:

$$\rho_0 D_a^{3} \cdot Cu(D_a) = D_g^{3} \cdot C_m^{0.1} \rho_m^{0.1} \cdot Cu \left[ \frac{C_m}{\rho_m} \right]^{0.1}$$

The Cunningham correction factor can be neglected for particles that have a diameter greater than 3 µm, since it is between 1 and 1.05 for a pressure equal to 1,013 hPa. This results in a simplified relationship between droplet diameter, aerodynamic diameter, solution mass concentration and salt density that is written:

$$\rho_0 D_a^{3} = D_g^{3} \cdot C_m^{0.1} \rho_m^{0.1}$$

(1) Characteristic diameter of a radioactive aerosol: 50% of the activity is contained in particles with an aerodynamic diameter less than the Amad.

(2) Characteristic adjustment time for particle speed vector after a change in direction or air flow rate.
Activity concentration, and thus the concentration of aerosols produced by the ultrasound pulverizers, remain stable for several hours. For example, activity concentration may be adjusted between 1 Bq/m³ and 200 Bq/m³ for aerosols marked with $^{137}$Cs and between 0.08 Bq/m³ and 12 Bq/m³ for those containing $^{239}$Pu. The reference for aerosol activity concentration is measured using sequential sampling on a FSLW Teflon filter manufactured by Millipore. The sample is taken in the air duct using an isokinetic probe with a controlled flow rate of 30 l/min. The activity collected on the filter is measured by counting using a proportional counter (MINI20, Eurisys, or equivalent) that distinguishes α and β radiation. The proportional counter is calibrated by comparison with an activity measurement, using liquid scintillation, on a filter containing radioactive aerosols. The scintillator is calibrated using a primary radioactivity standard provided by the Laboratoire National Henri Becquerel.

Table 1: Activity concentration (Bq/m³ STP) for aerosols marked with $^{239}$Pu measured by sequential sampling for three experimental configurations (STP: Standard conditions of Temperature and Pressure), each sampling period lasting approximately 20 minutes.

<table>
<thead>
<tr>
<th>Activity concentration (Bq/m³ STP)</th>
<th>18</th>
<th>16</th>
<th>14</th>
<th>12</th>
<th>10</th>
<th>8</th>
<th>6</th>
<th>4</th>
<th>2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference filter number</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 5 shows examples of the stability in activity concentration for aerosols marked with $^{239}$Pu. Relative expanded uncertainty ($k = 2$) for the activity concentration of each reference sample is approximately 3%. As seen in Figure 5, aerosol activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. For more significant activity concentrations (up to 200 Bq.m⁻³) obtained with $^{137}$Cs, dispersion over eight hours is only 5%. It should be noted that during the various tests, reference activity concentration is calculated over three-hour periods. In this case, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time. Over an eight-hour period, the variation coefficient of the measurements is between 13% and 14% for an activity concentration of approximately 5 Bq.m⁻³. As seen in Figure 5, the variation coefficient during the various tests, reference activity concentration is stable over time.

Channel for generating natural radioactive aerosols

The channel for generating natural radioactive aerosols on the ICARE test bench is shown in Figure 3. The facility can create a controlled atmosphere composed of naturally-occurring radioactivity, including gaseous radon-222 ($^{222}$Rn) and its four short-lived decay products. Radon is generated by three radium-226 ($^{226}$Ra) sources impregnated in felt [Guélin, 1993]. The felt is placed in different receptacles closed with glass frit. Fiberglass filters are placed at the inlet and outlet to prevent any contamination of the bench by $^{238}$Ra. An air flow rate of 1 l/min circulates in the receptacle in order to transport the radon emanated from the radium source. A valve system is used to select the radium source according to the radon activity required in the air duct. The air used is filtered and controlled to a relative humidity of 65% to optimize the radon emanation factor. A three-liter buffer tank is placed downstream from the radium sources, thus eliminating 90% of the $^{220}$Rn produced by the $^{226}$Ra impurities present in the $^{226}$Ra source.

The $^{222}$Rn is then placed in a 100-liter aging tank, where it is mixed with an inactive aerosol to obtain short-lived decay products with an attached fraction and a free fraction. The inactive aerosol is composed of CsCl. It is produced by an ultrasound pulverizer specific to this channel. The operating parameters for the aerosol generator are selected to produce an attached fraction that has an Amad equal to 0.2 µm. This diameter is considered representative of the attached fraction encountered in the environment for stable meteorological conditions (Amad between 0.1 µm and 0.5 µm).

Two filter sampling systems are located at the outlet of the aging tank to determine radon activity as well as the attached fraction and free fraction of the decay products. One of the sampling systems is equipped with a metal screen upstream from the filter to eliminate the free fraction in the sample (interception of nanometric particles because of their significant Brownian motion); the activity of each component is determined using the Thomas method(3)

Finally, the aerosol is continuously injected into the ICARE test bench air duct at a flow rate equal to 2.5 l/min. Activity concentration of radon decay products in the air duct can be adjusted between 1 Bq.m⁻³ and 300 Bq.m⁻³.

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(3) Interpretation of the change in filter activity over time taking into account decay periods of different radioactive isotopes.
5.1

Test results for two monitor types

The instrument response for radioactive aerosols gives the measurement accuracy for actual operating conditions. It is defined as the ratio between activity concentration indicated by the monitor and the ICARE bench reference activity concentration.

Figure 6 represents activity concentrations obtained with Monitor 1 for two aerosols marked with $^{239}$Pu with Amad values equal to 0.4 µm and 4 µm. Figure 6 also shows the reference activity concentration measured in the ICARE test bench duct. Figure 7 shows the same type of results for Monitor 2. These tests were performed for $^{239}$Pu activity concentrations between 2 Bq.m$^{-3}$ and 23 Bq.m$^{-3}$, representing 20 to 300 times the previous derived air concentration, and were carried out without introducing natural radioactive aerosols.

Monitor algorithms were set to obtain a response as quickly as possible. For both monitors tested, a measured point was obtained once every second. Parameter settings have an influence on how static primary data fluctuations are processed and cause oscillations that can be seen in Figures 6 and 7. Figure 6 also shows that when the filter was advanced automatically on Monitor 1 (activated when filter pressure loss becomes too high), activity concentration was stored in memory and the monitor continued measuring after an interval of approximately 25 minutes.

On the basis of these tests, it is also possible to calculate instrument response time as a function of the activity concentration present in the duct. Generally speaking, the lower the activity concentration, the longer the response time. For both monitors tested, response time was approximately 15 minutes for an activity concentration ranging from 10 Bq.m$^{-3}$ to 20 Bq.m$^{-3}$; for smaller values of about 4 Bq.m$^{-3}$, it increased rapidly up to 35 minutes. These values show that for a small release representing a low derived air concentration for $^{239}$Pu in aerosol form, the time expired before the monitor alarm is activated is approximately one hour.

Figure 8 summarizes the response R obtained for both monitors for different tests, first with aerosol Amad equal to 0.4 µm and 4 µm marked with $^{239}$Pu and $^{137}$Cs, and second with a mix of artificial radioactive aerosols ($^{239}$Pu or $^{137}$Cs) with Amad equal to 0.4 µm and natural radioactive aerosols ($^{222}$Rn decay product) with Amad equal to 0.2 µm. In these tests, the activity concentration of radon decay products (free fraction and attached fraction) was between 35 Bq.m$^{-3}$ and 42 Bq.m$^{-3}$ with an attached fraction rate of 75%. Response values were calculated over a period where the reference

![Figure 6](image1.png)

![Figure 7](image2.png)

![Figure 8](image3.png)
in aerosol collection efficiency. Determining collection efficiency as a function of particle size (or “sampling efficiency”), is thus essential for using the instrument to measure aerosols with a size distribution different from that used for calibration.

There are currently no experimental data on Monitor 1 collection efficiency, which is not the case for Monitor 2. Figure 9 shows the results of collection efficiency measurements as a function of Amad for Monitor 2 with a sampling bulb. Collection efficiency is defined by the relationship between activity concentration values determined by taking an off-line measurement on the monitor collection filter using the MINI20 proportional counter on one hand, and using the reference activity concentration from the ICARE test bench on the other.

Figure 9 shows that, for this bulb-equipped monitor, collection efficiency approached 100% for aerodynamic diameters between 0.15 µm and 4 µm. Conversely, collection efficiency decreased over 4 µm, reaching approximately 80% for particles with an aerodynamic diameter equal to 10 µm. This decrease could result from particles being deposited through impaction and sedimentation on the sides of the bulb.

Current monitors compensate for most of 222Rn decay product activity by using different types of algorithms. Figure 10, which illustrates an α energy spectrum measured for a mixture of 239Pu and 222Rn decay products, shows that compensation is necessary. The energy peak of 239Pu (5.2 MeV) overlaps the 222Rn short-term decay product peaks, especially 218Po (6 MeV) and, to a lesser degree, 214Po (7.7 MeV). The algorithms must therefore deconvolve the α energy spectrum in order to obtain actual 239Pu activity.

In Figure 8, there is no significant change in the response of the α and β channels on both monitors when the tests were carried out in the presence of a natural radioactive aerosol with Amad equal to 0.2 µm. These results demonstrate the efficiency of the radon decay product compensation method for measuring artificial radioactive aerosol activity concentration.

Consequently, variation in the response of the α and β channels as a function of particle aerodynamic diameter may be due to a change in aerosol collection efficiency. Determining collection efficiency as a function of particle size (or “sampling efficiency”), is thus essential for using the instrument to measure aerosols with a size distribution different from that used for calibration.

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5.1 Conclusion

The operation of continuous air monitors is complex: it calls on several physical mechanisms and mathematical processes to sample and collect aerosols, to detect specific radionuclides and to calculate activity concentration in real time. At present, this information cannot be modeled given the current state of knowledge, and instrument performance cannot be assessed based only on static tests using solid sources. The ICARE facility generates standard artificial and natural radioactive aerosols for calibrating continuous air monitors under real operating conditions.

Through this process, the response of instruments calibrated on the ICARE facility takes into account:
- sampling efficiency of the sampling head and aerosol deposit on the walls of the monitor air-flow system;
- aerosol penetration on the collection filter;
- self-absorption of α emission when the filter is clogged by aerosols;
- aerosol distribution uniformity on the filter surface;
- influence of radon decay products on the measurement of artificial radioactivity;
- effectiveness of the data processing algorithm.

The test methods designed for the ICARE facility were recognized by the IEC in 1996 and are mentioned in the IEC 60761 series and IEC 61578. In addition, IRSN’s Aerosol Physics and Metrology Laboratory is accredited by Cofrac’s testing section (accreditation no. 1-1243, available at www.cofrac.fr) for conducting dynamic tests on continuous air monitors.

The results of tests performed on the two types of monitor available at this laboratory show that the data processing algorithms correctly compensate the presence of radon-decay products in determining the activity concentration of artificial aerosols marked with $^{239}$Pu and $^{137}$Cs. The tests also reveal, however, that the monitors performed differently when measuring activity concentration in artificial aerosols marked with $^{137}$Cs and artificial aerosols marked with $^{239}$Pu for an aerodynamic diameter of 4 µm.

These results highlight the need to calibrate monitors in actual operating conditions using aerosols that are representative of each environment. The results also show that instrument response time can be very long (about an hour), depending on activity concentration, and must therefore be known to accurately determine the causes and consequences of an alarm that has been activated.
References


CURRENT RESEARCH ON HEPA FILTER CLOGGING by aerosols generated during a fire

IRSN and Areva NC are currently conducting a joint research program on fire that sets out to improve knowledge of HEPA filter clogging and to develop an empirical model of clogging of these filters by combustion aerosols. Inasmuch as possible, the model must be independent of fuel type and be suitable for integration in a computer code that processes the interaction between ventilation and fire. This article describes the influence of different “direct” factors such as filtration rate, deposited aerosol surface density, diameter of particles generated by combustion, and aerosol condensate content, as well as “indirect” factors such as the flow rate and oxygen concentration in the air supplying the fire, which affect changes in the air flow resistance of a clogged filter.

Fire risk analysis for a nuclear facility requires assessing the consequences of fire on the containment of radioactive substances and determining the quantity of radioactive material that may be released into the environment. Measures to be taken (compartamentalization and ventilation control, for example) to reduce the consequences require special studies. Among the ventilation equipment items at nuclear facilities designed to control contamination release, air-cleaning systems constitute a major component, especially the final filtering stage consisting of high-efficiency particulate air (HEPA) filters.

An outbreak of fire in a ventilated facility may cause not only heat stress, but also air flow stress and mechanical stress in air-cleaning devices due to pressure variations occurring during transient phases such as ignition and extinction. Aerosols must also be taken into account, since they affect the clogging of HEPA filters in the ventilation system. These aerosols are either the products of combustion or a combination of combustion products and contaminants.

The case studied here focuses on the most common case involving combustion aerosols only.

In a nuclear facility, filter clogging may have two harmful effects on containment integrity:

- it may cause a mechanical failure of the filtering medium and thus a partial or total loss of filter efficiency;
- it may cause a drop in air flow exhaust from the room where the fire is located, leading to local overpressure and disturbing the balance in the cascading vacuum zones throughout the facility. The most realistic way of assessing whether these effects may occur is by using qualified computer codes that process ventilation/fire interaction. This requires models that describe HEPA filter clogging.
Consequently, in the past several years IRSN and Areva NC have been conducting a joint research program to improve knowledge on fires and the interaction between fire and ventilation systems.

Operating conditions for research on filter clogging resulting from fire

Research on HEPA filter clogging set out to construct a clogging model that is independent of the fire scenario by taking into account only the "direct" clogging factors. For this purpose, IRSN used the "BANCO" test bench (Figure 1), specially designed for analytical experiments on HEPA filters clogged by aerosols generated by the combustion of different materials [Mocho and Laborde, 2002]. It features a compartment measuring approximately one cubic meter that contains the fuel loads. This compartment is connected to an exhaust duct equipped with a fan for air circulation. The duct is divided into two insulated channels in which the air flow rate varies respectively from 50 m$^3$/h to 100 m$^3$/h and from 50 m$^3$/h to 500 m$^3$/h. This configuration can be used to perform clogging tests at different filtration rates for the same combustion rate, thereby maintaining the same soot characteristics. A filtering box containing a HEPA filter was placed on each channel to study filter clogging.

The test bench instrumentation measured heat stress and air flow (head loss) stress on the HEPA filter being tested, and also determined the characteristics of fuel thermal degradation and the aerosols generated. For this purpose, the test bench was equipped with thermocouples placed between the fire and the HEPA filter being tested, as well as electronic pressure sensors to measure head loss across the filter terminals, and a balance to measure fuel mass loss. Aerosol mass concentration for air combustion was determined either by taking sequential samples on filters, or by using a dilution system (DEKATI FPS 4000) installed in series with a microbalance (R&P TEOM) for continuous measurement. The aerosol grain size distribution, between 30 nm and 10 µm, was measured after dilution using the DEKATI ELPI low-pressure granulometer.

Particle morphology was determined by examining transmission electron microscope slides from specific samples. Finally, water content and aerosol condensate content were obtained using the Karl Fischer method (by chemical titration) and by evaporation and drying in an oven.

In parallel, tests carried out on the DIVA facility (shown in Figure 2) determined how a change in scale affects the aerosols generated when electric components burn, and demonstrated the effect on HEPA filter clogging.

The DIVA facility is composed of four adjacent compartments and a modular ventilation network for studying different fire scenarios [Saux et al., 2005]. Using a bypass duct installed on the air exhaust network of the compartment containing the seat of the fire, HEPA filter clogging was studied at a filtration flow rate of 50 m$^3$/h. The instrumentation used in this duct (Figure 3) was equivalent to that found on the BANCO test bench and measures heat stress and air flow stress on the HEPA filter being tested, as well as the thermal degradation characteristics of the fuel and the generated aerosols. Additional temperature and pressure measurements were taken and further gas analyses were conducted in the compartment.
containing the seat of the fire. The filters studied in the two facilities mentioned above were pleated, double-dihted fiberglass HEPA filters manufactured by CAMFIL-FARR for use in nuclear facilities (reference 1501.37.00) with 6 m$^2$ of effective filtration surface area, and a nominal filtration flow rate of 450 m$^3$/h.

In the BANCO facility, different solid fuel materials were studied: polymethyl methacrylate (PMMA), commonly used in certain industrial facilities and featuring easy thermal degradation (absence of combustion residue) that is relatively well known, as well as Lexan and PVC, each combined at 33% and 50% (in mass) with PMMA, to promote combustion.

Characterizing filter clogging consisted of determining the change in airflow resistance R of the filter as a function of the mass $M_{ae}$ of the deposited aerosols. By analogy with a new filter, this resistance is usually defined within the scope of ventilation network modeling [Laborde et al., 1994] using the relationship $R = (\mu_0 \cdot \Delta P)/(\mu \cdot Q_v)$, where $\Delta P$ represents filter head loss (Pa), $Q_v$ the filtration volume flow rate (m$^3$/s), $\mu_0$ and $\mu$ dynamic fluid viscosity (Pa.s), at 20°C and at its filter temperature, respectively. While the tests were running, the filtration rate was kept constant during clogging.

These parameters are related to the filters (filter medium characteristics, pleating, and any pre-clogging required), the filtration air flow regime (filtration rate) and combustion products (deposited surface density, granulometry of elementary particles and aggregates, aggregate morphology, and water and/or condensate content). The second category includes "indirect" parameters (incident thermal flux, fire ventilation flow rate, air oxygen content and fuel type), which influence the "direct" parameters that characterize the combustion aerosols and were thus taken into account indirectly in the model.

*Figures 4 and 5 show the effects of filtration rate, ventilation flow rate and oxygen concentration [O$_2$] on HEPA filter clogging by aerosols generated through PMMA combustion."

A reduction in the filtration rate (Figure 4) led to an increase in the air flow resistance ratio $R/R_0$ of a pleated HEPA filter ($R_0$ being the air flow resistance of a new filter) for a given mass of deposited aerosols. This was primarily explained by the initial heterogeneity of air flow in a pleated filter and the arrangement of particles along the pleats, which led to a reduction in the useful filtration surface, the reduction increasing as the filtration rate decreased [Del Fabbro, 2001].

Moreover, an increase in the richness of the fuel mix (ratio between stoichiometric O$_2$ flow rate and available O$_2$ flow rate), characterized by a decrease in the oxygen flow rate or concentration [O$_2$] of the fire ventilation air (Figure 5), led to a reduction in the air flow resistance ratio $R/R_0$ for a given mass of deposited aerosols.

This was related to an increase in the size of the primary particles in the aggregates that make up the aerosols released by the combustion fire, hence the importance of accurately determining the characteristics of these aggregates [Mocho et al., 2007].

**Characteristics of released combustion aerosols**

The combustion aerosols released by the different types of fuel tested (PMMA alone, PMMA and Lexan combined, PMMA and PVC combines, or a mixture of components of the type found in an electrical cabinet) presented similar grain sizes for a combustion regime based on a lean fuel mixture (oxygen in excess). The aerosols released were composed of aggregates and primary particles. These aggregates showed significant polydispersion (a wide range of diameters), with a mass median aerodynamic diameter from 0.7 µm to 1.0 µm (low fire ventilation) and 1.5 µm to 1.8 µm (high fire ventilation) and a geometric standard deviation ranging from 3.5 to 5.
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Figure 4 Influence of filtration rate on filter clogging by aerosols generated through PMMA combustion.

Figure 5 Influence of combustion fire ventilation air flow rate and \([\text{O}_2]\) concentration on filter clogging by aerosols generated through PMMA combustion at a filtration rate of 0.23 cm/s.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ventilation flow rate (m³/h)</th>
<th>Fire compartment air renewal rate (per hour)</th>
<th>Combustion surface area (m²)</th>
<th>Overall mixture richness</th>
<th>Characteristic size (nm)</th>
<th>Mean water content (%)</th>
<th>Total condensate content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA (100%)</td>
<td>50</td>
<td>50</td>
<td>0.0625</td>
<td>0.5</td>
<td>51 ± 9</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>450</td>
<td>0.0625</td>
<td>&lt; 0.1</td>
<td>40 ± 8</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>PMMA/LEXAN (50%/50%)</td>
<td>50</td>
<td>50</td>
<td>0.0625</td>
<td>0.25</td>
<td>60 ± 12</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>450</td>
<td>0.0625</td>
<td>&lt; 0.1</td>
<td>48 ± 10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>PMMA/PVC (50%/50%)</td>
<td>50</td>
<td>50</td>
<td>0.0625</td>
<td>0.25</td>
<td>77 ± 16</td>
<td>17</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>450</td>
<td>0.0625</td>
<td>&lt; 0.1</td>
<td>59 ± 13</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>Electrical cabinet components</td>
<td>50</td>
<td>50</td>
<td>0.16</td>
<td>0.8</td>
<td>64 ± 17</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Electrical cabinet (DIVA Facility)</td>
<td>300</td>
<td>2.5</td>
<td>2.4</td>
<td>2</td>
<td>58 ± 9</td>
<td>not measured</td>
<td>&gt; 25</td>
</tr>
</tbody>
</table>

Table 1 Combustion aerosol characteristics as a function of experimental conditions.
However, while aggregate size and morphology [Ouf et al., 2008] were more or less similar, their clogging capability was different. This may be partly explained by the size difference in the primary particles making up the aggregates, and partly by their more or less “solid” or “liquid” nature, depending on water and condensate content. A “dendritic” structure (such as PMMA) offers greater resistance to air flow than a “spherical” structure. Similarly, liquid-type aerosols (fuel containing PVC for example) are less clogging than solid aerosols of the same size [Pénicot, 1998]. When the combustion regimen consisted of a rich mixture (oxygen starved), liquid-type aerosols contained a higher proportion of condensates due to the greater amount of unburned fuel vapor. Moreover, if the fire took place in a compartment with a low air refresh rate (as on the DIVA facility), the interaction between particles and unburned components could be significant enough to change aerosol morphology. The initial aggregates may be covered with “sludge” and completely lose their “aggregate” morphology in favor of a “compact particle” morphology, which may consist of both a solid phase and liquid phase.

Table 1 shows the characteristics of aerosols released for different mixtures and combustion conditions. As an illustration, Figures 6, 7 and 8 are transmission electron microscope photographs of particles from the combustion of PMMA and a PMMA/PVC mixture (50%/50% by mass) in the BANCO facility, and the combustion of an electrical cabinet in the DIVA facility. The aerosols in the BANCO facility consisted of aggregates of elementary particles, sized approximately 40 nm and 77 nm, respectively. In the DIVA facility, the particles were compact, measuring approximately 220 nm, and did not have an aggregate-type structure.

Clogging model

Given the complex mechanisms and parameters in HEPA filter clogging by combustion aerosols, the current state of knowledge cannot describe clogging through a phenomenological law. It seemed preferable to establish an empirical relationship from “direct” parameters instead.

Empirical clogging model for HEPA filters

In the initial empirical model [Mocho et al., 2004], the “direct” parameter for characterizing aerosols was the mass median aerodynamic diameter. Work recently carried out on the BANCO facility [Ouf et al., 2008] showed a correlation between the diameter of the primary particles that compose the aggregates, and the pair...
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where $R$ and $R_0$ represent the air flow resistance of the clogged filter and new filter, respectively (kg/s.m$^{-4}$); $M_{ae}$ the surface density of aerosols deposited on the filter (g/m$^2$); $T_c$ the water and condensate content of the deposited aerosols (%); $d_{pe}$ the mean diameter of the elementary particles contained in the aggregates or the equivalent volume diameter of the particle (m); $v$ the filtration rate (m/s); and $a$ and $b$ the model experimental constants (independent of fuel), where $a = 2.8 \times 10^{-8} \text{ m}^3/\text{g}$ and $b = 5.5 \times 10^{-21} \text{ m}^8/\text{g}^2\text{s}^2$.

of indirect parameters consisting of the "ventilation air flow rate and oxygen [O$_2$] concentration". Mass median aerodynamic diameter was thus replaced by the mean diameter of the primary particles in the aggregates (when the morphology of the combustion aerosol was the "aggregate" type) and by the equivalent volume diameter of the particle (when the morphology was not the "aggregate" type). Additionally, a factor that took into account the water and condensate content of aerosols deposited on the HEPA filter was added to the empirical clogging relationship. This was presented in the following form:

$$\frac{R}{R_0} = 1 + a \left( \frac{T_c}{700} \right) M_{ae} d_{pe} + b \left( \frac{T_c}{700} \right)^2 v d_{pe}^4$$

Figure 9  Comparison between model and experimental results on HEPA filter clogging by aerosols generated through PMMA combustion for different test conditions.

Figure 10  Comparison between model and experimental results on HEPA filter clogging by aerosols generated through combustion for different fuels.
The results obtained show that it is possible to describe HEPA filter clogging by aerosols generated during a fire involving solid fuels by using an empirical model that takes into account "direct" parameters (filter type, mass of aerosol deposits, characteristic size of released aerosols, water and condensate content and filtration rate). While this model is independent of the fuel used, it is only valid for combustion conditions that generate an aerosol whose "solid" quality is not significantly changed by the possible presence of condensates (total aerosol condensate content deposited on the HEPA filter $\leq 25\%$).

Inversely, when water content and condensate content are high, it is difficult to establish an empirical relationship for HEPA filter clogging that is independent of aerosol physico-chemical characteristics as well as condensate characteristics, which are directly related to the type of fuel. The outlook for progress in this field thus rests on determining the characteristics of the condensation phase and in understanding the interaction between unburned components and aerosols, which can significantly influence the type of aerosol released and thus HEPA filter clogging in actual fire conditions. It is also necessary to study the influence of variation in the filtration flow rate during the clogging phase, since work carried out to date has been conducted at a constant filtration rate.

**Conclusion**

Figure 9 shows that there was good agreement between the experimental results obtained from PMMA combustion and the proposed empirical model when condensate content was low ($T_c = 2\%$). In contrast, Figure 10 highlights the overestimate of clogging by the empirical model for a total condensate content of 35% (case of combustion of a 50% PMMA/50% PVC mixture); for lower concentrations ($2\% < T_c < 25\%$), the model correctly represented the experimental results. The deviation observed for the highest condensate concentration was explained by the fact that the deposit on the filter could no longer be considered as "solid" (Figure 8). Since the deposit of solid aerosols (dendrite formation) on the filter was different from a liquid aerosol (liquid bridge formation) (Pénicot, 1998), the proposed model was no longer valid.

In the case of a filter clogged by aerosols whose morphology was not the "aggregate" type (as is the case in under-ventilated combustion with strong interaction between aerosols and unburned components, where sludge is formed on the initial "aggregate"), final aerosol size was greater and its clogging capability much lower (for an equivalent mass deposit). As this aerosol tended towards the liquid state, its clogging capability also depended on physical parameters related to its chemical nature (viscosity and surface tension, etc.). The clogging model therefore had to be adjusted.

**References**

An initial version of the 900 MWe fire PSA was completed in 2003. This version evolved into the current "reference" version, which includes:

- modifications made subsequent to safety reviews associated with the third series of ten-year inspections of the 900 MWe plant units;
- the state-oriented approach to incident and accident operation deployed between 1990 and 2003 on the French nuclear power plant fleet. In contrast with the former "event" approach, based on predetermined operating strategies selected on the basis of initial diagnostics, the state-oriented approach applies iterative strategies prepared according to the physical and thermohydraulic state of the nuclear steam supply system;
- measures implemented in the fire-fighting action plan deployed on PWR units between 1997 and 2007 to improve facility fire protection (deterministic approach).

The objective assigned to the 900 MWe fire PSA was twofold. First, the assessment had to rank the rooms in the nuclear island according to their contribution to core melt risk (Level 1 PSA) in the event of fire. Second, it needed provide a probabilistic tool for each type of assessment related to fire risk on 900 MWe reactors.

To fulfill the first objective, the approach used for the 900 MWe fire PSA consisted of identifying the accident scenarios that may result from a fire (scenarios of damage to equipment and electric cables required in reactor operation) and assessing the frequency of core melt. IRSN then analyzed the main factors contributing to core melt frequency and assessed the design and operating measures implemented by the operator with regards to fire risks.
The first step of the 900 MWe fire PSA consisted of choosing, from the 826 rooms studied, the rooms with the greatest fire risk, which were then analyzed more closely. For this purpose, the 826 rooms initially selected were grouped into zones where a fire could ignite and propagate (no fire barrier between rooms).

Among these zones, which were analyzed based on simplified fire scenarios that could lead to core melt, only the “critical zones” meeting the following criteria were selected for detailed study:

- zones containing safety-related equipment;
- zones where loss of all equipment would lead to a partial or total loss of equipment essential for reaching safe shutdown;
- zones where the contribution to the global probability of core melt is non-negligible.

After applying this approach, 34 critical zones, or 57 rooms termed “critical rooms”, were retained for detailed study.

Methods

Method for selecting critical zones

The first step of the 900 MWe fire PSA consisted of choosing, from the 826 rooms studied, the rooms with the greatest fire risk, which were then analyzed more closely. For this purpose, the 826 rooms initially selected were grouped into zones where a fire could ignite and propagate (no fire barrier between rooms).

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Reference nuclear power plant unit and scope of study

The reference plant unit chosen was Unit 1 of the Blayais Nuclear Power Plant, which had served as EDF’s reference for implementing the fire-fighting action plan. The rooms studied in the 900 MWe fire PSA were those housing safety-related components (equipment and cables). In total, 826 rooms in ten buildings were initially chosen.

Following the conclusions of the 2003 version of the 900 MWe fire PSA, the current reference version was limited to the study of reactor states where the cooling system that cools the reactor during shutdown is not connected to the reactor coolant system, in other words, those operating states where the reactor is at power, which is when core melt occurs most frequently. Likewise, the reactor building was also not included in the study because fire risk in this location occurs essentially during maintenance periods when the reactor is shut down.

Finally, the control room was covered in a specific study separate from the reference 900 MWe fire PSA.
### Detailed study of critical rooms

The fire probability safety assessment of rooms identified as critical included two major phases:

- assessment of the frequency of equipment and electric cable damage:
  - assessment of fire frequency;
  - preparing and quantifying fire scenarios;
  - assessment of the time elapsed before equipment and electric cable damage;
  - assessment of core melt frequency;

- analysis of the functional consequences caused by loss of equipment and electric cables;
- modeling and quantification of accident sequences subsequent to the fire leading to core melt.

The flowchart in Figure 1 shows the different steps of the 900 MWe fire PSA.

---

### Table: 900 MWe Fire PSA

<table>
<thead>
<tr>
<th>Initiating event</th>
<th>Self-extinction</th>
<th>Fixed extinguishing system</th>
<th>Compartmentalization by doors</th>
<th>Compartmentalization by fire dampers</th>
<th>Detection</th>
<th>Fire-fighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>After fire outbreak</td>
<td>Opening manual valves</td>
<td>Sprinkler system</td>
<td>Door initially closed</td>
<td>Manually closing a door left open</td>
<td>Reliability of fire damper closing system</td>
<td>Manually closing a fire damper</td>
</tr>
<tr>
<td>Detection</td>
<td>Automatic detection</td>
<td>Extinction by first response team</td>
<td>Extinction by second response team</td>
<td>Extinction by fire brigade</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 2: Fire scenario event tree.
Assessment of equipment and electric cable damage frequency

Assessment of fire frequency
The fire frequency assessment was based on analysis of operating experience feedback on fires in French pressurized water reactors. To calculate fire frequency, 306 fire outbreaks were considered. They were classified into five categories according to origin: electrical, mechanical, hydrogen, maintenance work, and miscellaneous.

Preparing and quantifying fire scenarios
Preparing fire scenarios was based on constructing and quantifying event trees. The following events were considered:
- self-extinguishing fire;
- fire extinguished by fixed sprinkler systems;
- compartmentalization achieved using:
  - doors;
  - fire dampers;
- (automatic or human) fire detection;
- fire extinction using mobile means (nearby personnel, first response team, second response team, fire brigade).

Probabilistic assessment of the failure of these events was based on French operating experience on pressurized water reactors. The duration of each fire scenario (time required to extinguish the fire) was also the result of operating experience and depended on the detection and extinguishing configurations in each situation. Figure 2 shows the fire scenario event tree.

Assessment of time elapsed before equipment and electric cable damage
A fire simulation conducted using the FLAMME_S lumped-parameter code developed by IRSN was used to calculate ambient temperature changes as a function of compartmentalization and ventilation in the room containing the seat of the fire and in the adjacent rooms (connected either by openings or through the ventilation system). These calculations were used to determine the time elapsed before equipment and electric cable damage (thermal failure) occurred in the relevant room, and in the adjacent rooms in the case of propagation. This time interval ended the moment the following thermal failure criteria were met:
- for electric cables, the adopted failure temperature was 230°C (PEPSI 1 test cited in reference report [Rapport LEF, 1998]);
- for electric equipment, the adopted failure temperature was 40°C (maximum qualification temperature specified by the Design and Construction Rules for Electrical Components of PWR Nuclear Islands).

Assessment of equipment and electric cable damage frequency
After the two previous tasks, for each fire scenario, the time interval before damage ($t_{fc}$) was compared to the fire scenario duration ($t_{sc}$). When the first was less than the second, equipment and electric cables were considered damaged and the frequency associated with damage represented the fire scenario frequency.

Core melt frequency assessment

Functional analysis
For each of the equipment and electric cable damage scenarios based on a fire in one of the 900 MWe fire PSA critical rooms, functional analyses were carried out to identify whether the situation corresponded to a Level 1 “internal initiating event” PSA accident sequence.

The functional analyses identified:
- the principal functional consequences on the unit resulting directly from equipment and/or electrical cable damage;
- redundant equipment available to replace lost equipment;
- alarms and information available in the control room;
- operating procedures planned or imposed by complying with instructions selected by the operator or with technical operating specifications.

Modeling and quantifying accident sequences
Modeling of 900 MWe fire PSA accident sequences leading to core melt was based on Level 1 PSA modeling for events of internal origin.

In general, the same modeling assumptions (functional and thermohydraulic assumptions) retained for the “internal initiating event” Level 1 PSA were used for the fire PSA. The changes made in the fire assessment take into account:
- unavailability of equipment items required for accident management when they are destroyed by fire or fire has caused failure of these items;
- aggravating factors in quantifying human error in order to take into account operating difficulties in the event of fire. These operations may include:
  - problems in diagnosing the actual plant unit situation when information is not available or multiple alarms have been activated in the control room;
  - additional stress related to the fire;
  - difficulty in taking action locally (especially in the rooms near the room where the fire has broken out, due to smoke).
The IRSN study also measured the benefits of implementing the fire-fighting action plan and the state-oriented approach to operation. In comparison with the first version of the 900 MWe fire PSA issued in 2003, core melt frequency in the current reference version has been reduced by a factor of seven.

### 900 MWe fire PSA results

The study carried out by IRSN demonstrated the importance of fire-related risk. For 900 MWe PWR nuclear reactors, the total frequency of core melt events in the fire PSA represents one third of the core melt frequency established in the "internal initiating event" Level 1 PSA. This significant contribution of fire must, however, be qualified. Intentionally conservative assumptions and calculations were adopted in the absence of sufficient knowledge, especially for modeling electrical equipment combustion and estimating thermal failure temperatures.

The main results of the study may be summarized as follows:

- twelve rooms account for 99% of core melt frequency in the 900 MWe fire PSA. They are mainly electrical rooms containing safety-related equipment items that, if lost, could entail accident situations combined with difficulties in plant operation management;
- one room alone accounts for 31% of core melt frequency in the 900 MWe fire PSA. This room is characterized by high fire frequency due to the presence of numerous electrical cabinets, representing multiple sources of ignition. The preponderant scenarios lead to total loss of emergency power supply situations.

### Conclusion

Despite changes made on EDF’s PWR units, fire risk continues to contribute significantly to the total frequency of core melt. In addition, following the safety reviews for the third series of ten-year inspections on 900 MWe PWR plant units, EDF recognized the preponderant role of the room identified by IRSN and has committed to improving protection of equipment in this room. The considerable fire risk in question justifies further R&D at IRSN, including both experimental programs and modeling of the phenomena involved.

### References

5.4 IRSN DEVELOPS A PROBABILISTIC SAFETY ASSESSMENT of fire risk for 1,300 MWe reactors

Véronique BERTRAND
System Design and Operation Assessment Unit

Safety reviews related to the third series of ten-year inspections on 1,300 MWe PWR plant units will start in 2010. In preparation, IRSN is developing a Level 1 probabilistic safety assessment (PSA) of fire risk for 1,300 MWe reactors in order to establish its own independent opinion on the assumptions and results in the fire PSA that will be conducted by EDF.

The general method adopted by IRSN for its 1,300 MWe fire PSA in large part follows the fire PSA approach described previously and applied to 900 MWe reactors. Nevertheless, the lessons learned from the latter and progress in computer tools have led to certain changes.

In particular, IRSN has set out to identify and quantify the preponderant accident sequences leading to core melt. The study will therefore focus on the most critical equipment and rooms in terms of fire-related risks. Design and operating measures implemented by the operator will also be assessed.

The project will be entirely carried out using RiskSpectrum® software, thus giving overall coherence to the model, increased user-friendliness and facilitating sensitivity studies on the least robust assumptions. For fire modeling, the 1,300 MWe fire PSA will rely on SYLVIA, a software system for simulating fire, ventilation and airborne contamination phenomena recently developed at IRSN.

The failure criteria for electrical equipment constituted a sensitive issue in the 900 MWe fire PSA and must be adapted for the 1,300 MWe fire PSA. That is why IRSN prepared a test program on electrical cabinet component failures caused by heat effects (CATHODE tests in 2007 and 2008). Tests on failures due to smoke are also planned.

Ultimately, the study will provide a useful probabilistic tool for conducting targeted assessments by IRSN’s specialized services.
5.5

IRSN DEVELOPS A LEVEL 1 PROBABILISTIC SAFETY ASSESSMENT for the Flamanville 3 EPR

Julien DELACHE
Probabilistic Safety Assessment Unit

French nuclear reactor safety is essentially based on deterministic analyses. Probabilistic safety assessments (PSAs), based on a special investigation method, are conducted as a complement to classical deterministic analyses. PSAs consist of a series of technical analyses for assessing the risks associated with nuclear facilities in terms of the frequency of postulated initiating events and their consequences. On this basis, they help define and prioritize actions to be taken to reach and maintain a satisfactory safety level.

PSAs have become an essential tool for safety analysis. They are used regularly in IRSN technical opinions and occasionally during safety reviews of existing reactors or during new reactor design, such as the European Pressurized Water Reactor (EPR) project. In the latter case, they help define procedures and physical measures that guarantee a satisfactory safety level.

For the future technical review required for EPR commissioning, EDF must present an updated version of its Level 1 PSA, as well as "hazards" PSAs and the Level 2 PSA. To ensure the quality of its assessment, IRSN is developing its own Level 1 PSA for the Flamanville 3 EPR. It constitutes a counter-study that will estimate core melt frequency and its major factors, and will also facilitate sensitivity studies on EPR design assumptions and design options.

This PSA should also serve as a basis for IRSN’s development of "hazards" PSAs and a Level 2 PSA.
The issue of the hydromechanical consequences of delayed packing on water-saturated backfill was raised during IRSN’s examination of the 2005 Clay Study [Andra, 2005] on the feasibility of a deep radioactive waste repository in a clay geological formation. DSU report no. 106 indicates that “delayed convergence [should] tend towards a reduction of open volume in the backfilled structures. If these structures are saturated with water, depending on the kinetics of delayed convergence and surrounding hydraulic diffusivity, [...] the possibility of creating an additional hydraulic gradient under the effect of the delayed behavior of the rock and structures should be studied”. As for any phenomena that may change water flow regimes or radionuclide transfer conditions around structures, it must be studied to assess long-term storage safety.

The issue is a difficult one from a mechanical point of view because it must take into account coupling between delayed behavior and hydromechanical behavior in geomaterials on the scale of the structure. It is also raised outside the context of radioactive waste storage when the hydrogeological impact of post-closure behavior of an underground facility must be assessed. Studies on post-closure hydrogeology are found in the literature [Vermeulen and Usher, 2006, Oliver et al., 2006, Van Biljon et al., 2006] but there is little research on the hydromechanical interactions caused by closing a deep cavity [Xu and Genin, 1994].

Before initiating complex numerical modeling, IRSN was interested in researching analytical solutions to better understand the different mechanisms at work, find the best approach, assess the influence of the different parameters, and select a test case to reinforce subsequent, more sophisticated numerical models. The work was carried out in collaboration with the civil engineering and building department (URA 1652) at the École Nationale des Travaux Publics de l’État (national school for public civil engineering projects, ENTPE) and produced recently published original analytical solutions [Wong et al., 2008a and 2008b]. Further theoretical and numerical developments are still in progress.
This article briefly presents the mathematical approach adopted and the resulting analytical solutions. It then presents the results of a parametric study obtained using this analytical approach. The article also discusses other lines of research pursued by IRSN in the field of geomechanics and specifies their relationship with the question of post-closure hydromechanical behavior of underground structures.

Analytical equations for the case of a spherical cavity

The general problem described above was simplified by considering a spherical cavity(1) with a radius “a” located at great depth in a porous, water-saturated environment. Spherical coordinates are used, where “r” represents the distance to the center of the cavity and “t” is time. The unknown variables are the fields of radial displacement \( u(r, t) \), pore pressure \( p(r, t) \), and the stress tensor \( \sigma(r, t) \). The vectors and tensors are noted in bold type.

The behavior of the surrounding environment is considered poro-viscoelastic, i.e., typical of porous material whose response to mechanical loads is not instantaneous. At the initial moment \( t_0 \), the cavity is considered to be backfilled and in hydraulic equilibrium with the surrounding environment. A liner, intact at this moment, counteracts rock convergence. The state of surrounding stress is considered hydrostatic, of the form \( -\Sigma_0 \) where \( \Sigma_0 \) is total stress (i.e. the sum of effective stress and water pressure) and 1 is the tensor with a unit of order 2. Liner degradation is considered to begin from this instant.

Backfill behavior is considered poroelastic, with a bulk modulus \( K_B \). The backfill is assumed to be much more permeable than its surrounding environment and its pore pressure is thus considered uniform. At the initial moment, the backfill is saturated with water and is in hydraulic equilibrium with its environment. Effective stress \( \sigma_{\text{eff}} \) inside the backfill is considered null, which corresponds to null initial packing, a pessimistic assumption in terms of the amplitude of the hydromechanical transient expected during liner degradation. The liner, which at the initial moment ensures the mechanical equilibrium of the wall, absorbs the difference in effective stress between the backfill and the surrounding environment.

The liner itself was not modelled. Only the support pressure \( p_s(t) \) that it exerts on the wall was taken into account. This pressure decreases over time and, at this point in the study, the decrease is taken as \( p_s(t) = (\Sigma_0 - p_o) e^{-\kappa t} \) where “\( \kappa \)” represents degradation kinetics. The exponential form was chosen for its simplicity and the multiple possibilities that it offers in degradation kinetics, ranging from the perpetual liner \( (\kappa = 0) \) to instantaneous failure \( (\kappa = \infty) \). Ultimately, the work on coupling between leaching and the mechanical behavior of concrete [Nguyen, 2005; Torrenti et al., 2008b] carried out through IRSN-ENPC and IRSN-LCPC/ENS-Cachan joint research projects, will improve this representation using more advanced numerical models.

Modeling of viscous behavior in the surrounding environment was based on the work of [Coussy, 2004]. Two approaches, direct and functional, were considered.

In the direct approach, material behavior is described by the following relationships:

\[
\begin{align*}
\sigma &- \sigma_0 + (p - p_o) = K_s (e - e^0) + \frac{1}{2} \mu_s (\varepsilon - \varepsilon^0) \\
\sigma &- \sigma_0 + (p - p_o) = \frac{1}{2} \mu_s (\varepsilon - \varepsilon^0) + \frac{1}{2} \eta \varepsilon^0
\end{align*}
\]

where “\( \sigma \)” is average stress, “\( p \)” pore pressure, “\( e \)” bulk deformation, “\( \varepsilon \)” a raised index signifying a viscoelastic contribution, “\( s \)” the stress tensor deviator, “\( \varepsilon^0 \)” the deformation tensor deviator, and \( K_s, \mu_s, \eta \) are constants.

In the functional approach, the material behavior evokes the Stieltjes convolution product and the following relaxation functions:

\[
K(t) = K_s - (K_s - K_0) \exp \left( -\frac{t}{\tau_s} \right) H(t) ; \mu(t) = \mu_s - (\mu_s - \mu_\infty) \exp \left( -\frac{t}{\theta_s} \right) H(t)
\]

where \( K_0 \) and \( K_\infty \) are respectively the instantaneous and long-term bulk moduli of the solid skeleton, \( \tau_s \) and \( \theta_s \) are the characteristic relaxation time for bulk compression and shear, \( \mu_0 \) and \( \mu_\infty \) are respectively the instantaneous and long-term shear moduli, and \( H(t) \) is the Heaviside step function \( \{H(t \geq 0) = 1; H(t < 0) = 0\} \).

[Wong et al., 2008b] showed that these two approaches were equivalent for the problem investigated here. In the numerical applications presented in the fourth section of this article, preference has been given to using the functional approach notation. The characteristic time values for creep in bulk compression and shear, \( \tau_s \) and \( \theta_s \), are related to the previous parameters as follows:

\[
\tau_s = \frac{K_s}{K_0} , \quad \frac{\theta_s}{\mu_s} = \frac{\mu_\infty}{\mu_s} - 1
\]

(1) The geometry of a cylinder of infinite length would be more representative of tunnel geometry, but leads to more difficult solutions requiring Bessel functions. This case has nonetheless been resolved and an article on the subject is being published.
Lastly, the Laplace transform of the previous equation is transferred back into the general equation (EG-1), giving:

$$\frac{d^2}{dr^2} \left( p - p_0 \right) + \frac{2}{r} \frac{d}{dr} \left( p - p_0 \right) - q \left( p - p_0 \right) = 0 \quad \text{(EG-2)}$$

with $q = \frac{s}{\lambda_0 \omega(s)}$.

The boundary conditions are also written in the Laplace transform space. Assuming that water is not compressible, the first boundary condition expresses that cavity convergence is accompanied by expulsion of a volume of water equal to the reduction in cavity volume. It is presented below in two forms, the real form and the transformed form:

$$\frac{p(a,t)}{\partial t} = \frac{\partial u}{\partial t} + s \pi(a,t) \quad \text{(CL-1)}$$

The second expresses equilibrium of the excavation wall under the stress applied by the backfill, liner and outside environment:

$$-\sigma_{rr}(a',t) - \pi(a,t) = -\sigma_{rr}(a',s) + \frac{\sigma_{rr}(a',s) - \sigma_{rr}(a',t)}{s + \kappa} \quad \text{(CL-2)}$$

The negative sign of $\sigma_{rr}$ results from the convention for representing the “compression” state. The term $\sigma_{rr}(a',s)$ represents the backfill contribution and is expressed as a function of the unknown variables “$u$” and “$p$” at the wall in the following manner:

$$\sigma_{rr}(a',s) = 3 K_p \frac{\pi(a,t)}{a} - p(a,t)$$

where $K_p$ is the backfill bulk modulus. The term $\sigma_{rr}(a', t)$ represents the contribution of the surrounding environment and can also be expressed as a function of the unknown variables at the wall in a slightly more complicated manner explained by [Wong et al., 2008b].

The two general equations EG-1 and EG-2, completed with boundary conditions CL-1 and CL-2 and the initial conditions, completely define the mathematical problem for $r \geq a$. Although pressure appears uncoupled in EG-2, coupling strongly intervenes in boundary conditions. This system can be completely resolved in Laplace transform space. The solution is written as follows:

$$p - p_0 = \frac{\pi_0}{\lambda_0} \frac{\alpha_0}{r} e^{-\alpha_0 r} \text{ (S-1)}$$

Resolution in Laplace transform space

This chapter outlines the resolution method and the solutions obtained. A more detailed discussion can be found in [Wong et al., 2008a and 2008b].

Well-known for transforming differential equations into algebraic equations, the Laplace transform method was used. The Laplace transform $\tilde{f}(r,s)$ of a function $f(r,t)$ is defined by:

$$\tilde{f}(r,s) = \int_{0}^{\infty} f(r,t) e^{-st} \, dt$$

where $s$ is the transform parameter.

The problem considered in the domain $r \geq a$ (i.e. the surrounding environment) has two fields: radial displacement $u(r,t)$ and pore pressure $p(r,t)$. The first general equation of the problem is derived from the mechanical equilibrium equation of the surrounding environment, $\text{div} \sigma + \rho g = 0$, which is simplified here as $\text{div} (\sigma - \sigma_0) = 0$. Finally, after several transformations, this can be expressed as:

$$\text{div}[2u_0 (e^{-\epsilon}) + \left( K_0 (e^{-\epsilon}) - (p - p_0) \right) 1] = 0$$

Considering the Laplace transform of this equation and taking into account the assumption of the surrounding environment’s viscoelastic behavior, $(e^{-\epsilon})$ replaces $(e^{-\epsilon})$, resulting in:

$$\frac{\partial \tilde{u}}{\partial t} + \frac{p - p_0}{\omega_0(s)} \tilde{u} = \tilde{e} \quad \text{(EG-1)}$$

where $\omega_0(s) = K_0 (e^{-\epsilon}) + 4 \mu_0 \beta(s)$, $\alpha_0 = \left( 1/\tau_0 \right) + s$ and $\beta(s) = \left( 1/\beta \right) + s$.

The second general equation is derived from hydraulic diffusion and pore pressure. It is obtained as follows: the fluid mass conservation equation and Darcy’s law are written taking into account the initial hydraulic equilibrium condition. This gives:

$$\frac{\partial \tilde{p}}{\partial t} = \lambda_0 \Delta (p - p_0)$$

where $\phi$ is porosity and $\lambda_0$ the hydraulic conductivity of the surrounding environment. The usual assumptions on small deformations and incompressibility of the solid matrix then lead to:

$$\varepsilon = \phi - \phi_0$$

Last, $\frac{\partial \varepsilon}{\partial t} = \lambda_0 \Delta (p - p_0)$
Solution S-1 may also be expressed in a dimensionless form. The selected dimensionless (or “normalized”) variables are marked with an apostrophe and grouped in the following table:

\[
\begin{align*}
\tau' = \frac{\tau}{\tau_h} ; \quad \alpha' = \frac{\alpha}{\alpha_h} ; \quad \kappa' = \kappa \tau_h ; \quad \rho_0' = \frac{\rho_0}{\rho_0_h} ; \quad K_0' = \frac{K_0}{\rho_0 \tau_h} ; \quad \omega_0' = \frac{\omega_0}{\omega_0_h} ; \quad \theta_0' = \frac{\theta_0}{\theta_0_h} ; \quad \gamma' = \frac{\gamma}{\gamma_h} ;
\end{align*}
\]

The characteristic time \(\tau_h\) is selected so that

\[
\tau_h = \frac{\omega_0}{\lambda_h \alpha_0}.
\]

In particular, \(\omega' (s')\) and \(\Omega' (s')\) are written:

\[
\begin{align*}
\omega' (s') &= \frac{\omega_0}{\omega_0_h} ; \quad \Omega' (s') = \frac{\Omega_0 (s')}{\omega_0'}.
\end{align*}
\]

The dimensionless analytical solution in the Laplace transform space is therefore written:

\[
\begin{align*}
\mathcal{L}^{-1}\{\omega' (r', t')\} = \mathcal{L}^{-1}\{\omega_0 e^{-s_t} / \omega_0 (s')\} = \frac{1 - e^{-s_t}}{s_t} \mathcal{L}^{-1}\{\frac{\tau_h}{\alpha_0} \mathcal{L}\{\phi_0 (r', t', \Omega')\}\}
\end{align*}
\]

Returning to the “normal” space from the Laplace transform space is not simple. The general definition of the inverse of a Laplace transform is written:

\[
f (r, t) = \mathcal{L}^{-1}\{f (r, s)\} = \int_{s = 0}^{s = \infty} e^{-st} f (r, s) e^{st} dt
\]

and requires calculating an integral in the complex plane. When this calculation is not analytically possible, numerical algorithms like those of [Stehfest, 1970] or [Talbot, 1979] are used. This is how the parametric study in the following section was carried out.

Nevertheless, in the case of the spherical cavity discussed in this article, two particular cases exist where solution (S-2) may be inverted analytically. They are:

- the case where the behavior of the surrounding environment is simply poroelastic, i.e., without viscosity. This case was studied in detail by [Wong et al., 2008a]. It occurs again here as the time values characteristic of creep and relaxation tend towards infinity \(\tau_c, \tau_r, \theta_c, \theta_r\). The displacement field in the “normal” space thus takes the form:

\[
\begin{align*}
\mathcal{L}^{-1}\{\omega_0 (r', t') / \omega_0 (s')\} = \mathcal{L}^{-1}\{\phi (r', t', \Omega')\}
\end{align*}
\]

where functions \(g (r', t', \Omega')\) and \(\phi (r', t', \Omega')\) and constants \(A, B, C, D\) are given by [Wong et al., 2008a];

- the “general” poroviscoelastic case, modified by the following additional assumptions: \(\tau_c = \theta_c\) and \(\tau_r = \theta_r\). These assumptions are inspired by the results of the parametric study presented in the fourth section below. The displacement field thus takes the form:

\[
\begin{align*}
\mathcal{L}^{-1}\{\omega_0 (r', t') / \omega_0 (s')\} = \mathcal{L}^{-1}\{\phi (r', t', \Omega')\}
\end{align*}
\]

where the function \(\Lambda (r', t', \kappa')\) is given by [Wong et al., 2008b].

**Examples of applications: a parametric study**

The purpose of this article is to demonstrate the applicability of the analytical solution obtained in the general case of poroviscoelastic behavior in the surrounding environment, to visualize the mechanisms at work and assess the influence of various parameters. The analytical solution (S-2), written in the Laplace transform space, is numerically inverted using the Stehfest algorithm. The reference values of the parameters are as follows:

\[
\begin{align*}
\Sigma_0 &= 10 \text{ MPa}; \quad p_0 = 5 \text{ MPa}; \quad K_0 = 1,680 \text{ MPa}; \quad \mu_0 = 1,890 \text{ MPa}; \quad \kappa_R = K_0 / 30 = 56 \text{ MPa};
\end{align*}
\]

\[
\begin{align*}
K' = 2; \quad \tau_c' = 12; \quad \tau_r' = 4 \quad (\text{i.e. } K' = 560 \text{ MPa})
\end{align*}
\]

\[
\begin{align*}
\theta_c' = 6; \quad \theta_r' = 2 \quad (\text{i.e. } \mu_0' = 630 \text{ MPa})
\end{align*}
\]

which leads to the following dimensionless parameters:

\[
\begin{align*}
P'_0 = 0.5; \quad K'_0 = \Sigma_0 / p_0 = 168; \quad \mu'_0 = \mu_0 / p_0 = 198; \quad K'_R = 5.6
\end{align*}
\]
These values are only possible orders of magnitude for the various parameters and must not be considered as “established” for conducting any safety studies relative to the Meuse/Haute-Marne site.

The results are given in their dimensionless form. Figure 1 shows the change in pore pressure, displacement at the wall and effective stress for five radii \( r' = r/a = 1, 1.1, 1.3, 1.6 \) and 2.5). The change in pore pressure reaches a peak then returns to its initial value. The closer to the cavity, the greater the peak value and the shorter the time required to reach it. The displacements in Figure 1b are expressed in relationship to the asymptotic displacement of the excavation wall, so that they vary within the interval \([0, 1]\). Stress stabilizes much more quickly than displacement, which explains a time scale limited to \([0, 3]\) in Figures 1c and 1d. This point should be highlighted because it shows that, for long time periods, creep occurs under practically constant stress. For effective stress, radial compression decreases as circumferential compression increases due to liner degradation. Asymptotic behavior depends to a great extent on backfill compressibility. In the present case, this compressibility explains the low, but non-null, effective radial stress on the excavation wall for extended time periods.

Figure 2 shows the effect of liner degradation kinetics \( \kappa' \) on circumferential pressure and stress. It confirms the essential role of this parameter in the study. For high values of \( \kappa' \), which represents a semi-instantaneous failure of the liner, pore pressure at the excavation wall changes instantaneously to the initial hydrostatic stress value \( \Sigma_0 \) or \( \rho' = 1 \) before returning slowly to its initial value. In contrast with effective radial stress, change in effective circumferential stress is not flat and shows a very localized maximum that appears for short periods, with a peak that becomes sharper and higher as the value of \( \kappa' \) increases. Viscous effects are entirely defined by the four characteristic time periods \( (\tau'_c, \theta'_c, \tau'_r, \theta'_r) \), the letter \( \tau \) referring to bulk compression, \( \theta \) to shearing, and indices \( c \) and \( r \) respectively to creep and relaxation. To simplify the study, these parameters were grouped in pairs: \( (\tau'_c, \tau'_r) \) and \( (\theta'_c, \theta'_r) \). For each pair, the two components were multiplied together and then multiplied successively by a factor of \( k = 1, 2, 5, \infty \), the other parameters remaining at the reference value indicated in Table 2.

Figure 3 shows the change in normalized pore pressure at a fixed point located near the wall \( r' = 1.1 \). Figure 3a highlights the influence of the pair \( (\tau'_c, \tau'_r) \) and Figure 3b that of the pair \( (\theta'_c, \theta'_r) \). This illustration shows that the variations of the pair \( (\tau'_c, \tau'_r) \) (i.e. the characteristic time periods of creep and relaxation in bulk compression) have little effect on the pressure field. The same holds true for the stress and displacement fields.

This may be explained by the fact the stress induced in the surrounding environment by pressure applied on the excavation wall is essentially deviatoric, as shown in Figure 4. Average, total and effective stress variations are less than 5% of the initial hydrostatic stress \( \Sigma_0 \) while deviatoric stress variations \( \sigma'_{ir} - \sigma'_{ii0} \) can reach 70% (Figure 1). This observation justifies the assumption \( \tau'_c = \theta'_c \) and \( \tau'_r = \theta'_r \) mentioned in the third section above to simplify the analytical inversion of the Laplace transform.

The last parametric study concerns the compressibility effect of backfill \( K_R \) and liner degradation kinetics \( \kappa' \). Figure 5 shows the change over time of pore pressure at one point \( (r' = r/a = 1.1) \) for different normalized bulk moduli of backfill \( K'_R = 0, 50, 168 \) and 504. The first value \((0)\) corresponds to the absence of backfill (cavity filled only with water) and the last to backfill three times steeper than the surrounding environment. The liner degradation kinetics are \( \kappa' = 2 \) in Figure 5a and \( \kappa' = \infty \) (instantaneous failure) in Figure 5b.

The influence of these two parameters is clearly significant, as confirmed in Figure 6, which shows change as a function of the deviatoric stress time period \( (\sigma'_{ir} - \sigma'_{ii0}) \) with \( r' = 1.1 \) for the same values of \( K'_R \) and \( \kappa' \). The results show that the maximum value of deviatoric stress may be reached during the transient phase, which could not be demonstrated using simplified approaches based only on two elastic calculations performed using short- and long-term parameters.
Figure 1  Change as a function of time and different radii ($r' = r/a = 1, 1.1, 1.3, 1.6$ and $2.5$) of: a) normalized pressure field $p/\Sigma_0$; b) normalized displacement field $u/u_\infty$; c) normalized effective radial stress $(\sigma_{rr}+p)/\Sigma_0$; d) normalized effective circumferential stress $(\sigma_{\theta\theta}+p)/\Sigma_0$.

Figure 2  Change as a function of time at the excavation wall ($r' = 1$) and for different liner degradation kinetics ($k' = 1.5, 20, 100$ and $500$) of: a) normalized pressure field $p/\Sigma_0$; b) effective circumferential stress $(\sigma_{\theta\theta}+p)/\Sigma_0$. The other parameters are set to the reference value given in Table 2.
Figure 3 Change in pore pressure as a function of time with $r' = 1.1$: a) bulk compression creep and relaxation time ($\tau'_c, \tau'_r$) are successively multiplied by a factor $k = 1, 2, 5, \infty$; b) the same applied to shear creep and relaxation time ($\theta'_c, \theta'_r$).

Figure 4 Change as a function of time with $r' = 1.1$ of: a) normalized average total stress; b) normalized average effective stress ($\sigma' + p'$). The different curves correspond to the increasing values of creep and relaxation time ($\theta'_c, \theta'_r$) defined as in Figure 3b using parameter $k$.

Figure 5 Change in pore pressure as a function of time with $r' = 1.1$ for different normalized backfill moduli $K'_R = 0, 50, 168$ and 504 with: a) $\kappa' = 2$ and b) $\kappa' = \infty$ (instantaneous liner failure).
Conclusions

During the review of the 2005 Clay Study, the issue of post-closure hydromechanical behavior of underground structures was raised. In a joint research effort, IRSN and CNRS/ENTPE investigated this subject and found original analytical solutions.

The underground structure under consideration was a deep spherical cavity assumed to be closed and backfilled, where liner degradation took place in the course of time. In the case of poroelastic behavior in the surrounding environment, the analytical solution can be completely explained. In the more difficult case of poroviscoelastic behavior in the surrounding environment, the solution is entirely explained in Laplace transform space and may be returned to "normal" space, subject to additional assumptions assessed for validity. The solution obtained in the Laplace transform space may also be used directly, in a general manner, using numerical inversion algorithms.

This analytical approach improves our understanding of the mechanisms at work and provides a very useful test case to support more advanced calculations that could be performed using computer code. It confirms the possibility of creating an additional hydraulic gradient under the effect of delayed rock and structural behavior, the consequences of which remain to be assessed in terms of water flow and radionuclide transfer around the structures. Finally, the approach can also be applied to parametric studies, as seen in the example given here.

This parametric study shows that, for the geometry under consideration, the characteristic time periods for creep and relaxation in bulk compression in the surrounding environment have little effect on the results. It also indicates that extrema in pore pressure and stress changes may be reached during the hydromechanical transient, which could not be revealed through a simplified analysis based on only two elastic calculations with short- and long-term parameters. Finally, it demonstrated that the most significant transients are generally obtained with high liner degradation kinetics and flexible backfill, confirming the key role of these two parameters and expressing their relative importance.

Acknowledgements

The author wishes to highlight the contribution of Dr. Chin Jian Leo from the University of Western Sydney (Australia) to the work presented in this article.
5.6

References

KEY EVENTS and dates

DISSERTATIONS DEFENDED

March 21, 2008
- Cynthia COLLEMERE submitted a thesis entitled "When designers incorporate organization in achieving risk control: two projects to modify high-risk chemical facilities" in Paris.

May 20, 2008

May 30, 2008
- Denis MARCHAND submitted his thesis entitled "Study on washout of fission products in aerosol form by pulverizing water droplets generated by a PWR spray system" in Saclay (near Paris).

October 2, 2008
- Roger ABOU-KHALIL submitted his thesis on "Characteristics of the electric charge of a natural radioactive aerosol" in Strasbourg.

December 3, 2008

OTHER KEY EVENTS

January 2008
- SERENA Project Phase 2 launched
  The second phase of the OECD’s SERENA (Steam Explosion Resolution for Nuclear Applications) project was launched on January 15-16, 2008 at the Nuclear Energy Agency in Paris during follow-up meetings on the project. SERENA is designed to assess the understanding of vapor explosion phenomena in a pressurized water reactor and investigate the potential of numerical tools in the field. The second phase of the project, which will last until 2011, will study the fuel/coolant interaction phenomenon when it occurs outside the reactor vessel.

  The preliminary meetings approved the work program and laid out conditions for performing the first tests in 2008. A new unit called AWG (Analytical Working Group), complementary to the Program Review Group and the Management Committee, was set up to develop computer codes in preparation for the tests, to interpret results, and adapt them for use with nuclear reactors. The next round of meetings will take place at the Korea Atomic Energy Research Institute (KAERI) in the Republic of Korea on October 15 and 16, 2008 when the initial test results and their interpretation will be discussed.

- Charles Motzkus awarded the Jean Bricard Prize
  On Wednesday, January 16, 2008, Charles Motzkus, a former IRSN doctoral student, was awarded the Jean Bricard Prize for his dissertation work on investigating particles suspended upon impact with droplets. This dissertation, written between 2004 and 2007 at the Aerosol Physics and Metrology Laboratory (LPMA), was defended at the University of Paris XII on December 14, 2007. This prize recognizes young researchers for their significant and original contributions to aerosol science.

June 2008
- IRSN participates in the National Center for Industrial Risk
  A research partnership agreement was signed at the end of last April by eight scientific organizations, including IRSN, that have complementary skills in the field of industrial risk control. The purpose of the agreement is to organize research and technology transfer activity within the PNRI, a national industrial risk cluster created by the State in 1998 and located in Bourges. Direction of research and technology transfer projects was entrusted to the Bourges Higher National School of Engineering (ENSIB).

  The convention will strengthen this technology center, dedicated to technology risk control, by encouraging joint projects with various partners and sharing knowledge to benefit businesses working in various fields such as explosives, hydrogen, monitoring of systems and operating safety, and crisis management. More precisely, IRSN will be involved in research on physical phenomena associated with wave propagation following an explosion and their interaction with infrastructure.