5.2. **Phenomena liable to result in early containment failure**

5.2.1. **Direct containment heating**

5.2.1.1. **Introduction**

The phenomenon of direct containment heating (DCH⁴) is diagrammatically represented in Figure 5.12. In the event of a PWR core melt accident, a corium melt composed of uranium and zirconium oxides as well as non-oxidised metals (zirconium and steel) and various fission products may form in the lower head. If the lower head ruptures in this situation, the corium is ejected, along with steam and, in some cases, hydrogen from the RCS and liquid water still present in the reactor vessel head when it fails. Depending on the internal pressure of the reactor vessel when it ruptures, this causes more or less finely-grained corium fragmentation and more or less widespread dispersion of the fragments outside the reactor pit. Corium dispersion leads to very efficient heat exchange between the corium and the gases present, as well as oxidation of metallic components of corium, producing hydrogen as a result. The oxidation is mainly due to the steam present in the RCS but also to the steam contained in the containment. The temperatures reached by the gases in the containment and the presence of very hot corium particles then triggers the combustion of the hydrogen created through oxidation of the dispersed corium. This combustion could cause the hydrogen already present in the containment to ignite at the time the reactor vessel ruptures if the concentration is high enough. These phenomena cause the containment atmosphere to heat up and its pressure to rapidly build up (in a few seconds), resulting in the containment being damaged or its integrity failing. In addition, the loads directly applied to the reactor vessel (thrust due to the gases and liquids leaving the reactor vessel, and pressure in the reactor pit) may result in a more or less significant movement of the reactor vessel itself, possibly causing a shock to the structures, the RCS and the SCS and the possible bypass of the containment if breaks are induced in the exterior of the containment, in a system connected to the RCS and not isolated from it.

The risk of the containment rupturing as a result of the gases inside the containment being directly heated is assessed from a technical point of view, assuming that there is no water in the reactor pit when the reactor vessel ruptures. Tests have shown that the risk of combustion is greater when there is no water in the reactor pit. If there is a large quantity of water in the reactor pit, the main phenomenon that can threaten containment integrity is the steam explosion that could occur when the reactor vessel ruptures as a result of the very hot corium coming into contact with the water in the reactor pit; the subject of steam explosions is discussed in Section 5.2.3. In the case of the reactors in operation in France, if there is no water in the reactor pit when the reactor vessel ruptures, this is because the Containment Spray System (CSS) was not operating before the reactor vessel ruptured. For the PWRs, the objective of “practical elimination” of the steam explosion risk in the reactor pit requires the reactor pit to be kept dry before the reactor vessel ruptures.

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4. The acronym DCH (Direct Containment Heating) is generally used.
5.2.1.2. Physical phenomena

Although the phenomena involved in DCH are well understood at the qualitative level, many uncertainties remain regarding the corresponding detailed physical phenomena and their importance in the pressure build-up within the containment [1, 7]. The extent and consequences of DCH greatly depend upon reactor geometry and an experimental approach has been preferred for some time, coupled with the development of simplified models for interpreting the test results and extrapolating them to the case of a power reactor. The particularly violent nature of the phenomenon and the highly specific conditions under which nuclear reactor core melt accidents occur demand the use of simplified geometries and materials and modest instrumentation in the tests, however. Most of the information obtained in experiments is global (corium dispersion rate and pressure peak), includes significant uncertainties (corium oxidation rate and hydrogen combustion) and is often result of analyses performed after the tests are conducted (dispersion and grain size distribution, for example). With the recent development of simulation tools and computational capabilities, certain phenomena can now be assessed in greater detail. All of these phenomena, including dispersion, metal oxidation, hydrogen combustion and the presence of water, have not yet been combined in CFD modelling, however, and it seems difficult to envisage doing so in the short term.

Figure 5.12 shows a diagram of the phenomena and the associated risks. When the reactor vessel ruptures, it contains, apart from the structural elements still in place,
a mixture of steam and hydrogen, some corium in the lower head and possibly some water, all of which is subjected to a pressure ranging from the operating pressure of the RCS (approximately 160 bar) to a pressure close to that of the containment (a few bar) if the RCS is completely depressurised. The corium and the steam, and possibly some hydrogen, are ejected under pressure into the reactor pit in different phases (single-phase liquid corium jet, followed by a two-phase corium and gas jet and a gaseous jet). The characteristics of their ejection, of course, depend on the size, shape and location of the break in the reactor vessel wall. The characteristics of the break are currently difficult to predict and so are uncertain (Section 5.1.3).

When the corium is ejected under pressure, it is fragmented into liquid droplets that rapidly oxidise, producing hydrogen. A flow of steam, hydrogen and corium then forms in the reactor pit. This highly complex flow is greatly influenced by the geometry of the reactor pit. It is also central to the following phenomena: the projection of corium onto the reactor pit walls, the formation of a liquid film along these walls and the entrainment and fragmentation of the film by the gases. All these phenomena increase the pressure of the gases in the reactor pit relative to that of the containment. As a result, part of the corium is entrained by the steam into the areas adjoining the reactor pit and towards the containment dome, while another part remains trapped in the pit. During this phase, the gases and the corium droplets interact both thermally and chemically. The gases’ temperature and pressure in the reactor pit therefore increase considerably. Hydrogen combustion is not possible in the reactor pit, however, because its atmosphere contains little oxygen (it was driven out by the gases leaving the reactor vessel). When hot gases and corium particles enter the containment, they contribute to the superheating and rapid pressurisation of its atmosphere. The greater the mass of corium dispersed and the finer its fragmentation, the greater the containment pressure build-up. The distribution of corium in the different areas of the containment and the duration of the flow also play an important role in defining the pressure build-up. Furthermore, when the very hot gases and corium particles enter the containment they provoke hydrogen combustion. This combustion is highly complex because it combines turbulent diffusion flames (in the containment area into which the jet leaving the reactor pit spreads) with premixed flames (in the containment areas outside the jet). In most situations, hydrogen combustion does most to heat up and pressurise the containment gases.

It should be noted that the above description of DCH and its current modelling has been simplified compared with reality for various reasons including the following:

– the presence of water, both in the reactor vessel and in the reactor pit, affects the phenomenon in various ways by creating the opposite effects. The water present in the reactor vessel, which is strongly depressurised when it ruptures, very rapidly vaporises (referred to as “flash vaporisation”). This causes the reactor vessel to depressurise more slowly, on the one hand (increasing the corium dispersion time), and causes a greater thrust upon the reactor vessel, on the other hand. This water does not entirely vaporise, however, and the water present in the reactor pit also disperses and so, firstly, acts as a heat sink and, secondly, disrupts or even inhibits combustion. As a result, it is difficult to know whether the presence of water has a generally beneficial effect or not;
as a result of the pressure in the reactor pit, the water can move and so modify
the geometric configuration and close flow routes or open others.

Technically, therefore, the problem is very difficult to model precisely.

5.2.1.3. Experimental programmes

The existing knowledge of phenomena involved in DCH has mainly been gained
through test programmes conducted on mock-ups, which provide small-scale reproduc-
tions of the main geometrical characteristics of reactors. The different geometries stu-
died are presented in the following paragraphs, after which the results of the tests are
discussed, based on the temperature and materials used to simulate the corium and the
presence of water in the reactor pit.

In the late 1980s and early 1990s, many tests were conducted on more or less
detailed mock-ups of American reactors at scales varying from 1/40 to 1/25 [1-4]. The
most widely studied and documented geometry is that of the ZION reactor. The link
between the reactor pit and the containment dome (through which the gases and
corium pass via the annular passage around the reactor vessel) was not represented
in the purpose-built mock-up of the Zion reactor in the Sandia National Laboratory’s
Surtsey facility in the United States (Figure 5.13). An instrumentation tunnel repre-
sented the connections between the reactor pit and the intermediate compartments
of the containment. In addition, the system simulating the reactor vessel was posi-
tioned outside the containment. The integral tests were conducted at high pressures
(around 60 bar).

![Diagram of the Zion reactor and its representation in the experiments conducted in
the Sandia National Laboratory's Surtsey facility.](image)

Figure 5.13. Diagram of the Zion reactor (left) and its representation in the experiments conducted in
the Sandia National Laboratory’s Surtsey facility (right) [1].
The second geometry studied was that of the Surry reactor. Some of the corresponding tests took into consideration the annular passage around the reactor vessel, directly linking the reactor pit with the containment dome, and the presence of thermal insulation around the reactor vessel. A limited number of experiments have been conducted with this geometry. Lastly, a third geometry, that of the Calvert Cliffs reactor, was studied; in this geometry, there is a larger annular passage around the reactor vessel, whose configuration is more like that of the French reactors.

In 1997, KAERI (South Korea) conducted a test campaign for IRSN (IPSN at that time). These tests were the first to study the DCH phenomenon, albeit solely in cold tests, in a geometry similar to that of a French 900 MWe reactor at a 1/20 scale.

More recently, tests were conducted in the DISCO facilities of Forschungszentrum Karlsruhe (FzK), now called Karlsruhe Institut für Technologie (KIT), in Germany [5, 7]. The initial test facilities, referred to as DISCO-C, were used to conduct cold tests, whereas another, referred to as DISCO-H, was used to conduct integral tests simulating all of the thermal and chemical phenomena. The DISCO facilities, which were initially constructed for studies on the PWR reactor (1:18 scale), were then modified so that the geometry of the 1300 MWe P’4 reactors could be studied (in collaboration with IPSN, Figure 5.14), for that of the KONVOI reactors (German reactors whose geometry is similar to that of the PWRs) and for that of the VVER-1000 reactors (a single test in DISCO-H). The PWR and KONVOI geometries are unusual as their reactor pit is very small, encouraging corium dispersion outside the reactor pit, particularly as there is no access corridor; in the case of the 900 MWe and 1300 MWe French reactors (Figure 5.14), the reactor pit is much deeper and there are three possible exit routes from the reactor pit: to the upper part of the containment (dome), to the compartments at the bottom of the containment and to the reactor pit access corridor. The DISCO tests were limited to reactor vessel internal pressures below 25 bar.

► Low-temperature simulant tests (dynamic aspects)

These tests aim to establish correlations relating to the entrainment of the simulant to the compartments adjacent to the reactor pit and to the containment based on experimental parameters, which generally consist of the size of the break in the lower head, the internal pressure of the reactor vessel when it ruptures, and the physical properties of the corium simulant and of the carrier gas leaving the reactor vessel. Various simulants have been used for the tests of this type: water (Figure 5.14), oils, Wood metal (a eutectic alloy composed of bismuth, lead, tin and cadmium) and gallium. The latter two simulants offer the advantage of possessing properties (density, viscosity and surface tension) that are similar to those of corium, whereas water is a poor simulant (its physical properties are very different from those of corium, and its phase changes — evaporation or freezing — are unrepresentative of it).

The KAERI tests, whose geometry is representative of that of the 900 MWe French reactors, have shown that when the internal pressure of the reactor vessel is high enough, up to 80% of the simulant can be entrained into the annular space around the reactor vessel and into the passage towards the containment dome, and then released
into the containment. In this geometry, the passage to the intermediate compartments of the containment is in fact very small and most of the fuel is ejected into the containment. In the case of the 1300 MWe reactors, a smaller fraction of the fuel is dispersed into the annulus (60%), as a substantial proportion of the fuel (~30%) is trapped in the reactor pit access corridor. Of the 60%, approximately 20% is directly entrained towards the containment dome and the rest is entrained into the intermediate compartments of the containment.

The geometry of the EPR reactor pit is very different. Due to the very small volume of the reactor pit, almost all of the corium may be drawn into the containment even if the internal pressure of the reactor vessel is very low (a few bar). The geometry of the EPR reactor pit has changed since the DISCO tests were conducted on EPRs and no longer includes a direct passage between the reactor pit and the containment; most of the ejected corium would then be entrained towards the intermediate compartments of the containment housing the equipment (SGs and pressuriser). The effect of various lower head rupture modes (break in the centre of the lower head, lateral break or partial de-capping of the lower head) upon simulant ejection dynamics has also been studied in tests on EPR geometries [6]; these tests have shown that greater masses are dispersed in the case of central breaks.

**High-temperature integral tests**

In addition to the dynamic aspects, these tests provide an insight into heat exchange phenomena and chemical interactions. Table 5.3 lists all integral tests conducted until 2010. The most frequently-used simulant in tests of this type consists of an iron and alumina
mixture \((\text{Al}_2\text{O}_3)\) resulting from a thermitic reaction\(^5\), with small quantities of chrome and zirconium sometimes added. Some tests have also been conducted using a composition more similar to that of an actual corium (containing a \(\text{UO}_2 + \text{ZrO}_2\) mixture). The main differences between thermite (\(\text{Fe-Al}_2\text{O}_3\)) and corium are their density (approximately 4000 kg/m\(^3\), compared with 8000 kg/m\(^3\)) and their oxidisable metal composition (Fe, compared with Zr + Fe + Cr). Consequently, the results of the tests conducted using thermite cannot be directly extrapolated to the case of a DCH incident. Many tests have been conducted in the United States, mainly by the Sandia laboratories (SNL) and Argonne laboratories (ANL), for three types of geometry (principally that of the Zion reactor, the Surry reactor and the Calvert Cliffs reactor) and different experimental conditions \(^1\). These tests were conducted using high reactor vessel pressures between 60 and 120 bar: as a result, dispersion of the simulant and the pressure build-up within the containment were both high.

In the case of Zion reactor geometry, the different tests (conducted using the Surtsey mock-up with no direct connection between the reactor pit and the containment dome\(^6\)) showed that the intermediate compartments of the containment retained 90% of the simulant and that there was a limited containment pressure build-up of approximately 2.5 bar (Figure 5.15). On the basis of these results, the US NRC has estimated that, in the case of this reactor, the risk of the containment rupturing as a result of DCH was zero \(^8\).

### Table 5.3. Main experimental programmes studying DCH.

<table>
<thead>
<tr>
<th>Series</th>
<th>Number of tests</th>
<th>Scale</th>
<th>Geometry</th>
<th>(\Delta P) (bar)</th>
<th>Material</th>
<th>(D_{\text{break}}) (^{(4)}) (m)</th>
<th>Direct connection with dome</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCH/WC(^{(1)})</td>
<td>7</td>
<td>1/10</td>
<td>Zion</td>
<td>26–67</td>
<td>\Fe-Al_2O_3\</td>
<td>0.4–1</td>
<td>No</td>
<td>Pit</td>
</tr>
<tr>
<td>TDS/LFP(^{(2)})</td>
<td>13</td>
<td>1/10</td>
<td>Surry</td>
<td>25–40</td>
<td>\Fe-Al_2O_3-Cr</td>
<td>0.4–0.9</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>IET-Zion(^{(3)})</td>
<td>9</td>
<td>1/10</td>
<td>Zion</td>
<td>60–70</td>
<td>\Fe-Al_2O_3-Cr</td>
<td>0.4</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>IET-Surry(^{(4)})</td>
<td>3</td>
<td>1/6</td>
<td>Surry</td>
<td>120</td>
<td>\Fe-Al_2O_3-Cr</td>
<td>0.7–1</td>
<td>Depending on the test(^{(5)})</td>
<td>Pit</td>
</tr>
<tr>
<td>ANL-IET(^{(5)})</td>
<td>6</td>
<td>1/40</td>
<td>Zion</td>
<td>57–67</td>
<td>\Fe-Al_2O_3-Cr</td>
<td>0.4</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>U(^{(6)})</td>
<td>3</td>
<td>1/40</td>
<td>Zion</td>
<td>30–60</td>
<td>\text{UO}_2 + \text{ZrO}_2 + \text{Zr}-stainless steel</td>
<td>0.4</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>CE-CES(^{(7)})</td>
<td>7</td>
<td>1/10</td>
<td>Calvert Cliffs</td>
<td>40–80</td>
<td>\Fe-Al_2O_3\</td>
<td>0.4–0.5</td>
<td>Yes</td>
<td>Reactor vessel</td>
</tr>
<tr>
<td>DISCO-H(^{(8)})</td>
<td>6</td>
<td>1/18</td>
<td>EPR</td>
<td>8–22</td>
<td>\Fe-Al_2O_3\</td>
<td>0.5–1</td>
<td>Depending on the test(^{(9)})</td>
<td>No</td>
</tr>
<tr>
<td>DISCO-FH(^{(9)})</td>
<td>5</td>
<td>1/16</td>
<td>P’4</td>
<td>15–25</td>
<td>\Fe-Al_2O_3\</td>
<td>0.5–1</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>DISCO-KH(^{(10)})</td>
<td>2</td>
<td>1/18</td>
<td>Konvoi</td>
<td>20–25</td>
<td>\Fe-Al_2O_3\</td>
<td>1</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Sandia NL, \(^{(2)}\) Argonne NL, \(^{(3)}\) FzK, \(^{(4)}\) reactor vessel break diameter relative to the scale of the reactor vessels concerned, \(^{(5)}\) study of the effect of the thermal insulation, depending on whether it remains in place or not.

5. When an iron oxide and aluminium are brought into contact, a highly exothermic chemical reaction occurs in which the aluminium reduces the iron oxide to produce what is called “thermite”, an iron and alumina mixture \((\text{Al}_2\text{O}_3)\); the reaction raises the temperature of the mixture, resulting in it melting.

6. In reality, there is a connection between the reactor pit and the dome in the reactor, but this has been ignored.
The various subsequent tests, including those conducted in the DISCO facility, suggest that when no combustion occurs (due to the inert atmosphere in the containment), the compartmentalisation of the containment plays an important role in DCH and only the simulant fraction dispersed into the containment dome effectively heats its atmosphere. This is because the thermal equilibrium is reached more rapidly in a small volume, as the ratio between the volume of corium and the volume of gas is greater and so the gases are heated more rapidly.

The chemical phenomena of oxidation and combustion play a key role in DCH. The first tests to study the effect of these phenomena are the IET tests conducted for the Zion and Surry reactors’ geometries (in most cases, with no direct connection between the reactor pit and the containment dome). In these tests, there was initially a moderate hydrogen concentration of approximately 2–3% in the containment. The metals were always very intensely oxidised. Hydrogen combustion rate was around 70%, resulting in the pressure doubling or tripling within the containment (Figure 5.15, left).

The DISCO-H tests confirmed these experimental findings \[7\]. They also showed that the oxidation not only occurs with the steam initially present in the reactor vessel, but also with the steam present in the containment (this could not be observed in the IET tests conducted with no direct connection between the reactor pit and the containment dome). Hydrogen combustion rate is very high in these tests — around 80% for initial hydrogen levels of 4.5–6%. Above all, they showed that there is a linear relationship between the pressure build-up in the containment and the estimated quantity of hydrogen contributing to combustion (Figure 5.15, right). If there is considerable hydrogen combustion, therefore, the heat transfers between the corium and the gas play a smaller

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**Figure 5.15.** Influence of combustion upon the pressure build-up in the containment. Left: comparison of the pressure build-up observed for an atmosphere with and without hydrogen combustion in the IET-Zion tests (Sandia NL) \[1\]. Right: relationship between the pressure build-up and the estimated quantity of burnt hydrogen (per unit of volume) for a selection of DISCO (FzK), CE and IET tests (Sandia, IET6-8: Zion geometry, IET9-11: Surry geometry) \[7\]. The line represents the theoretical envelope values of the pressure build-up linked with hydrogen combustion.
role in DCH. This can be explained by the fact that the gas heating up due to combustion limits the thermal transfers between the corium droplets and the gas.

In addition, the DISCO tests conducted using the geometries of the PWR and 1300 MWe reactors show that the effect of compartmentalising the containment is less marked if combustion occurs. The combustion itself is less sensitive to compartmentalisation with high hydrogen concentrations (5–6%). When the initial hydrogen concentration is low (less than 3%), however, combustion has difficulty in propagating to the regions that the corium has not entered.

► Tests with real materials

Following the IET tests using thermite, three similar tests were conducted using a mixture of UO$_2$, Zr, ZrO$_2$, Fe and Cr in the COREXIT facility (1/40 scale mock-up of the Zion reactor) in order to demonstrate the effect of using real materials in place of thermite. Very little data is therefore available on tests using real materials, and only very partial conclusions can be drawn from these tests.

Two tests were conducted using an almost inert containment atmosphere, eliminating all hydrogen combustion as a result; corium oxidation was possible, however, as the reactor vessel had a high steam content. For these two tests without combustion, which were conducted using a material whose specific energy is lower than that of thermite (approximately 1.2 MJ/kg, in the case of actual corium, instead of 2.7 MJ/kg for thermite), the pressure build-up in the containment dome was lower than in the tests conducted under similar conditions using thermite. The production of hydrogen due to oxidation of the materials by steam was much greater for corium, with corium oxidation of around 70%, compared with only 30–40% for thermite. This strong oxidation is mainly due to oxidation of the metals of which the corium is composed. Uranium dioxide (UO$_2$) can also be “superoxidised” by steam if enough is present; this “superoxidation” is probably limited, however, and produces little hydrogen.

In these two tests, it is also probable that corium oxidation was limited by the quantity of steam contained in the reactor vessel, which was insufficient to oxidise all of the oxidisable component materials of the corium. These tests therefore show that very high corium oxidation can occur for coriums whose compositions are representative of those that would form in a PWR core melt accident. For power reactors, a conservative approach to processing DCH consists in supposing that all the metals in the corium are completely oxidised when they are dispersed and ignoring uranium dioxide oxidation.

► Effects of the presence of water

The effect of water being present when the reactor vessel ruptures, either in the reactor vessel or in the reactor pit, has also been studied in the United States. The small number of tests conducted, coupled with the lack of even simplified models, only allows qualitative interpretations to be made, however. In the CE-CES tests (Calvert Cliffs reactor geometry, [4]), the corium simulant was initially in the bottom of the reactor pit, and water or steam that had previously been pressurised to between 40
and 80 bar was ejected from the reactor vessel through a break 4 cm in diameter (corresponding to a 40 cm diameter when scaled up to the real size of the reactor vessel). When the water was initially saturated (and so flash-vaporised on leaving the reactor vessel), this was not seen to have a significant influence upon the pressure build-up in the containment; the pressure build-up due to the water vaporising was therefore offset by a reduction in the effects of combustion and oxidation (approximately 30%). When the water temperature was close to the ambient temperature (meaning that the water did not vaporise on depressurisation), a significant drop (of around 30%) in the pressure loads was seen. In the CE-CES tests in which water was present in the reactor vessel, approximately 60% of the simulant was entrained towards the containment dome through the annular space.

Several tests were conducted by adding a small quantity of water in the reactor pit (the WC and IET tests). Some IET-Zion tests were also conducted using various quantities of water in the reactor pit. In these tests, the pressure build-ups were similar to those observed in tests with no water in the reactor pit; the presence of water therefore does not seem to have any overall effect upon the pressure build-up. The temperature measurements established that 50% less hydrogen was burned up than when there was no water in the reactor pit; in this case, therefore, the pressure build-up is largely due to water vaporisation. As a result, the presence of water has a very considerable effect upon the phenomena occurring in DCH and so could affect the pressure build-up under conditions different from those of the test. The current studies are based on the experimental results, however, and, as no adequate modelling is available, ignore the effect of the presence of water.

The presence of water in the reactor vessel or reactor pit seems fairly beneficial to DCH by limiting hydrogen combustion, although this must be confirmed by more detailed studies. When water is present, however, a steam explosion resulting from the interaction between the fragmented corium and the water may occur. Considering the measures taken to limit the possibility of high-pressure corium ejection in the event of a power reactor core melt accident (consisting of intentionally depressurising the RCS, see Section 4.3.3.3) and, therefore, the possibility of DCH occurring, conducting steam explosion studies is considered a priority in terms of risk mitigation.

The Sandia laboratories in the United States have conducted experiments in which molten corium was ejected at high pressure in a 1:10 scale mock-up of a flooded reactor pit (SPIT/HIPS experiments) [15]. In every case, a steam explosion destroyed the reactor pit in the tests. Details of the research results regarding the steam explosion are provided in Section 5.2.3.

### 5.2.1.4. Modelling

The complexity of DCH prevents it from being modelled in detail by coupling all of the important phenomena (corium ejection and fragmentation, heat transfers, oxidation of the component materials of the corium, hydrogen combustion and the presence of water).
Until the middle of the 2000s, the only existing models were constructed from simplified models mainly based on experimental correlations that were themselves implemented in “integral” computer codes used to calculate more or less complete accident sequences (MELCOR, MAAP, CONTAIN, ASTEC, etc.; see Chapter 8). These simplified models are mainly parametric, and their purpose is not to study and precisely understand the phenomena occurring in a DCH incident. They reflect the state of knowledge of these phenomena and can be coupled to provide a complete, albeit approximate, means of studying the progression of an accident.

For some years, FzK then IRSN have been conducting studies using multiphase, multidimensional simulation codes (the AFDM and MC3D codes, respectively). Unlike the parametric models discussed above, these computer codes represent certain important aspects of DCH more precisely, notably corium geometry and behaviour at different scales, but they do not represent the coupling of all phenomena. Furthermore, they process the complex chemistry occurring during DCH in a very simplified form. The AFDM and MC3D computer codes firstly aim to provide the parametric models with more appropriate correlations.

The modellers are now mainly focusing their attention on questions regarding corium dispersion. The experiments conducted show that both the oxidation of corium component materials and the hydrogen combustion are very closely linked with corium dispersion, and the simplified approaches producing envelope estimates of their effects upon the oxidation and combustion pressure do not excessively overestimate the pressures reached.

5.2.1.4.1. Parametric models

The DCH module of the US CONTAIN computer code [9] is the most advanced 0-D code available, and offers many computational options. Thus it also highlights the difficulties involved in modelling corium dispersion in DCH, as more than a dozen models or correlations may be used to describe how the corium debris is transported and the flows take place between the compartments of a containment, as well as describing how the structures trap debris.

The DCH module of the CONTAIN code contains relatively mechanistic models for describing how the corium is fragmented and the corium debris is entrained. It assesses the convection and radiant heat transfers between the debris and the atmosphere by means of conventional heat exchange laws. The code processes the chemical reactions involved in corium oxidation as well as in the combustion of hydrogen (both that produced through DCH and that already existing in the containment). Hydrogen combustion is evaluated by means of a simplified approach. Although the DCH module of the CONTAIN code provides a solid basis for qualification [10], its use is limited to US Zion or Surry reactors (GRS found it difficult to use when interpreting the results of the DISCO tests, which consisted of PWR and P'4 geometries) [11, 12]; this may be due to software complexity (notably its large choice of options) and, therefore, the need for its users to be highly experienced.

The other integral codes used to analyse core melt accidents adopt simpler approaches. The DCH module of the MAAP code, for example, uses correlations (based on the
Development of the core melt accident

gometry) to evaluate the total fraction of the dispersed corium [12]. The corium droplets are assumed to be in dynamic and thermal equilibrium with the gases. The distribution of droplets in the different outlets of the reactor pit then depends on the gas flow rates that the code computes for each outlet. Although this type of modelling can hardly be used to process precisely the geometry (notably that of the outlets) and the flows in the outlets (which depend on their geometry), it nevertheless offers the advantage of being simple.

The ASTEC computer code evaluates the pressure loads due to DCH by means of the RUPUICUV, CORIUM and CPA modules (see Chapter 8). The reactor pit phenomena are addressed by means of the RUPUICUV module. The CPA thermal-hydraulics module, which is used to compute the gas flows within the containment, cannot directly handle the special DCH phenomena associated with the presence of corium particles (heat transfers from the corium particles to containment gases, and corium oxidation), and an intermediate module — the CORIUM module — serves as an interface and processes corium energy contributions for use by the CPA module itself. The total dispersed fraction of the corium is determined using correlations. IRSN plans to revise the DCH modelling while still maintaining a simplified approach. Notably, it will introduce new correlations deduced from the results of the DISCO tests and the modelling conducted using the MC3D computer code.

5.2.1.4.2. Simulation software

IRSN and KIT have chosen to use multiphase thermal-hydraulics simulation codes to improve the state of knowledge of flows during DCH and simplify the development of simple models [13].

KIT uses the AFDM computer code, which was initially developed for conducting safety studies on fast neutron reactors (FNRs). This is a forerunner of the SIMMER III computer code, to which physical models relating to DCH have been added in order to simulate the chemical reactions between the metals and the steam or oxygen, for example, or else hydrogen combustion in the containment (parametric simplified model). The code processes gas flow configurations and thermal transfers between the gases and the corium in a comparatively comprehensive way, including the formation of corium films and crusts on the reactor pit cavity walls. Its use is limited to axisymmetrical 2D geometries, however. Promising results have been obtained for interpreting the DISCO tests conducted using the geometries of the EPR and Konvoi reactors; in particular, it has enabled IRSN to perform comparative analyses with the MC3D computer code.

The MC3D code is developed by IRSN and CEA; it is mainly used to evaluate the pressure loads caused by a steam explosion (Section 5.2.3). It can, however, also process many multiphase phenomena including — partially — DCH. This code is distinctive in that it describes the corium in detail: the “droplet field” (dispersed corium) is handled separately from the “jet field” (continuous corium) (see Figure 5.33 in Section 5.2.3, which illustrates this point). A detailed model of corium fragmentation and droplet coalescence allows users to move from one field to another. It includes a corium oxidation model. The MC3D code does not handle combustion, however. As combustion is the main contributor to the pressure build-up in the containment, the studies conducted
using the MC3D code only address corium dispersion and aim to develop simplified dispersion models for the ASTEC computer code and the probabilistic safety assessments (PSAs). The MC3D code can also be used to perform 3D computations that handle the French reactors’ special geometries more precisely. As an example, Figure 5.16 shows a reactor geometry processed using the MC3D computer code (simplified P’4) as well as the computed results for corium dispersion in the annulus, as a function of the internal pressure of the reactor vessel.

As well as providing a direct comparison of the computational results at several experimental points, this type of code can be used to study, by means of many computations and fairly coarse meshes, the sensitivity of corium dispersion to parameters such as the internal pressure of the reactor vessel, the gas temperature and the break size. A correlation for processing corium dispersion has therefore been developed on the basis of the DISCO test results. This correlation predicts, for example, that when water is used as the simulant, the threshold pressure (minimum) resulting in dispersion is around 5 bar (see also Figure 5.16). In the case of P’4 reactors, the studies show that, for a reactor vessel break approximately one metre in diameter, the corium dispersion threshold pressure (minimum) is around 20 bar and the pressure above which maximum corium dispersion occurs is around 40 bar. Figure 5.17 shows these results, based on the internal pressure of the reactor vessel for three break diameters (the size of the break is not known precisely; it can vary from a few centimetres to a metre, as described in Section 5.1.3).

It has also been observed, again for the P’4 reactors, that the cross-section of the reactor pit access corridor only affects the maximum quantity of corium dispersed in the containment; the other characteristics such as the dispersion threshold pressure are barely affected. This has been confirmed by additional DISCO experiments.

![Figure 5.16](image)

**Figure 5.16.** Left: 3D geometry used when interpreting the DISCO tests conducted using the geometry of the P’4 reactors (simplified geometry) processed by the MC3D code. Right: MC3D code evaluation of the fuel fraction dispersed towards the top of the reactor pit compared with the results of the tests conducted using water as the simulant and a reactor vessel break diameter of 60 mm.
The great weakness in the existing models concerns hydrogen combustion. The combustion computer codes cannot compute corium dispersion and oxidation; conversely, the MC3D and AFDM codes do not include an adequate combustion model. It appears necessary to model combustion if these computer codes’ predictive abilities are to be improved. Work on this point began in 2009 in the European SARNET system, under the supervision of KIT, with the aim of determining the most appropriate models and the way of introducing them into the multiphase simulation codes.

5.2.1.5. Summary and outlook

It is not easy to study the DCH risk. The risk is different for each type of reactor and, for a given geometry, depends on factors including the following:

– the internal pressure of the RCS at the moment the reactor vessel ruptures;
– the size of the break in the reactor vessel;
– the quantity of unrecombined hydrogen still present in the containment and in the RCS when the reactor vessel ruptures;
– the quantity of unoxidised metal in the corium.

The surest way of avoiding or limiting the effect of DCH upon the containment is to intentionally depressurise the RCS. This is incorporated into the design of PWR and AP1000 reactors. Depressurising the RCS is generally considered to be a key action in PWR safety during operation, notably in the Severe Accident Management Guidelines. Figure 5.17 shows the benefits of depressurising the RCS for the P’4 reactors and undoubtedly more generally, taking into account the uncertainties listed above, for all of the reactors in operation in France. DCH at a reactor vessel internal pressure of less
than 10 bar seems impossible for these reactors. Depending on the hydrogen concentration present in the containment, the corium melt outside the reactor vessel may result in hydrogen combustion without DCH in such a situation. The pressure loads on the containment would then only be due to hydrogen combustion.

The experimental data also show that the consequences of DCH are essentially related to reactor pit geometry and to the routes between it and the other areas of the containment. In particular, it is accepted that the consequences of DCH are reduced in reactors with no direct route for the corium and gases between the reactor pit and the containment dome; this solution has notably been chosen for the PWR reactors.

The combustion of the hydrogen created through oxidation of the corium dispersed by steam and of any initially present in the reactor vessel as well as in the containment atmosphere appears to be the main phenomenon responsible for building up the pressure in the containment. A detailed knowledge of the constituent metals of the corium as well as of the hydrogen quantities present in the containment and in the reactor vessel is needed to be able to evaluate precisely this pressure build-up. In situations in which there is considerable corium dispersion (dispersion of 30–50 tonnes of liquid corium; depending on the envisaged core melt accident scenarios, 100 tonnes or corium or even more may be dispersed), the studies conducted by IRSN show that containment mechanical strength limits may be reached during the resulting hydrogen combustion.

DCH is difficult to model. This is because the complexity and diversity of the phenomena involved in DCH, coupled with their dependence upon reactor building geometry, do not lend themselves to simple modelling. Parametric studies have been developed and used to conduct studies to estimate the pressure build-up in the containment during DCH, but their usefulness is highly doubtful outside their precise fields of validation (notably concerning the geometry of the reactor pit and the adjoining compartments). Multi-phase simulation codes have been used to obtain important results, notably concerning corium dispersion depending on the internal pressure of the reactor vessel. These are also difficult to use, however, and they cannot precisely determine all consequences of DCH in 2015, notably because of the difficulties of modelling corium oxidation and particularly, hydrogen combustion. In addition, the meshes used to process the complex real geometries are quite crude, and some geometric details cannot be modelled without simplification, resulting in inaccuracies in the flow computation.

The impact of water present in the reactor vessel or in the reactor pit during DCH has not really been characterised either. A better knowledge of this effect is necessary, but this can only be achieved by developing models coupled in a simulation code such as MC3D.

It appears necessary to use more precise simulation codes to compensate for the lack of experimental results (notably using real materials) and the limitations of the correlations developed on the basis of the existing results as well as to allow the results to be extrapolated to the case of a power reactor; this is why IRSN began development to improve DCH modelling for the French nuclear reactors in the middle of the 2000s.
5.2.2. **Hydrogen risks and means of mitigating their consequences**

5.2.2.1. **Introduction**

In the context of core melt accident studies on pressurised water reactors (PWRs), “hydrogen risk” is defined as the possibility of containment integrity being lost in a reactor or its safety systems as a result of hydrogen combustion. The hydrogen is principally produced through oxidation of the metals present in the reactor core (mainly the zirconium contained in the cladding of the fuel elements) during the core degradation phase (Section 5.1.1), and oxidation of the metals present in the corium pool or in the basemat during the molten corium-concrete interaction phase (Section 5.3). The hydrogen produced in this way is released into the containment. The hydrogen distribution in the containment is more or less homogeneous depending on the degree to which the atmosphere is mixed (this is mainly linked with the convection loops resulting from steam condensation within the containment). If it is heterogeneous, there may be local hydrogen concentrations that exceed the flammability limit of the gaseous mixture; if it ignites, this may result in pressure loads that can threaten containment or safety component integrity. The distribution and concentration of hydrogen within the containment may also be modified by the use of safety systems, such as the Containment Spray System (CSS), which homogenise the containment atmosphere and lead to an increase in hydrogen concentration due to steam condensation on water droplets. Moreover, systems such as recombiners and igniters already installed inside the reactor containments may affect hydrogen distribution by avoiding hydrogen building up in part or all of the structure (the PWRs in operation in France are only equipped with recombiners).

5.2.2.2. **Physical phenomena**

When a PWR core melt accident occurs, the hydrogen released from the RCS enters the containment atmosphere, which initially mainly consists of air and steam. In this atmosphere, convection movements are caused by the presence of steam and its condensation on cold surfaces. The hydrogen then plays a role in increasing the natural convection movements due to its low density and in reducing steam condensation on the walls by hindering steam diffusion. Convection within the containment may therefore be altered, and it is important to know whether the entire contained volume is set into movement as a result. If it is, the hydrogen and the air mix rapidly enough for it to be assumed that, outside the regions in which the gases are released and near to the walls, the atmosphere is homogeneous. Otherwise, only part of the contained volume — probably the upper part of the containment — is mixed, and the homogeneity of that part of the containment atmosphere is initially concerned; if its volume is small, that part can contain a gas mixture that is relatively rich in hydrogen. The hydrogen will then migrate more slowly (over the course of several hours, given the containment geometry and compartmentalisation) to the “dead” regions, which are probably in its lower part. In these regions, the hydrogen will be incorporated into the gas mixture, but the hydrogen level of the mixture will never exceed that found in the homogeneous region.
The flammability of the gas mixture in the containment depends on the temperature, pressure and composition of the mixture, as well as its ignition mode. In practice, however, the position of the point representing the composition of the mixture (hydrogen, air and steam) in the Shapiro diagram (see Figure 5.18) can be used to determine whether the mixture is flammable. In this diagram, the ignition and detonation regions are bounded by curves: the flammability limit curve bounds the flammability region, and the detonation limit curve bounds the detonation region. The detonation region, which is smaller, is within the flammability region. The flammability and detonation limits depend on the temperature and pressure; furthermore, the detonation limit is not an intrinsic characteristic of the gas mixture; it is only valid for the geometry in which it is obtained.

In a mixture flammable, combustion may be triggered by an energy source of a few millijoules. Consequently, in the presence of electrical power sources or hot points, it seems probable that ignition would occur rapidly once the gas mixture enters the flammability domain. In contrast, more energy (at least 100 kilojoules) is required to trigger a stable detonation. This explains why direct detonation can be ruled out for practical purposes; the only mechanism considered likely to provoke detonation is flame acceleration and the deflagration-to-detonation transition. In fact, due to hydrodynamic instabilities and turbulence (primarily caused by obstacles in the path of the flame), an initially laminar deflagration (with a flame velocity of around 1 m/s) may accelerate. Rapid combustion conditions may also develop, involving rapid deflagration (a few hundred m/s), deflagration-to-detonation transition (DDT) and detonation (over 1000 m/s). These explosive phenomena pose the biggest threat to the mechanical integrity of the containment walls, as they can produce very large, localised dynamic loads. The higher the combustion speed, the higher the pressure peak, albeit with a shorter peak application time.

Figure 5.18. Shapiro diagram for the hydrogen, air and steam mixtures.
Due to the large volume and geometric complexity (mainly due to its compartmentalisation) of the containment, it is currently not possible to perform predictive computations concerning flame acceleration. Based on their understanding of the mechanisms involved, researchers have nevertheless developed prerequisite criteria, i.e. conditions required for the various combustion modes. Two types of criteria have been defined in this way:

- the criterion “$\sigma$” concerns the flame acceleration; the value $\sigma$ is the expansion factor of the mixture, the relationship between the cold gas and burnt gas densities at a constant pressure, and so is an intrinsic property of the mixture in question; the critical value $\sigma^*$ above which flame acceleration is possible depends on the initial temperature of the gases and the stability of the flame and has been determined using the results of many experiments at different scales and in different geometries;
- similarly, the necessary conditions have been established for assessing the possibility of a deflagration-to-detonation transition (DDT); these are based on comparing a length typical of the geometry of the studied chamber with the size of the detonation cells (marked $\lambda$) characterising the sensitivity of the mixture.

These criteria were initially established for homogeneous gas mixtures and then extended to cover mixtures in which there are hydrogen concentration variations, on the basis of ENACCEF programme results (Section 5.2.2.3.2). These criteria are used to determine the situations presenting a rupture risk to the containment for which it appears necessary to compute the loads resulting from possible combustion, by studying the hydrogen distribution in the containment (taking into account its geometry). It should be noted that before these criteria can be applied, the codes used to compute the hydrogen distribution in the containment must be validated based on situations representative of core melt accident conditions; this has been the aim of experimental programmes on hydrogen distribution in recent years.

### 5.2.2.3. Experimental programmes

#### 5.2.2.3.1. Hydrogen distribution

Hydrogen distribution in the containment is controlled by various coupled complex physical phenomena, such as:

- the flows in the release region and the transporting of gases in the containment, notably hydrogen and steam;
- natural convection induced by temperature differences between the atmosphere and the walls and by density differences between the various gases present;
- steam condensation on the containment walls and internal structures;
- heat and mass stratification of the gases;
- diffusion in flows and turbulence;
- the effect of spray droplets on flows or of steam condensation on spray droplets.
Many analytical experiments have studied these phenomena separately. Regarding condensation, for example, the Dehbi experiments on natural convection, together with those of Tagami, Uchida and Huhtiniemi on forced convection, have enabled global models for steam condensation to be developed. The resulting correlations are more or less dependent on the test conditions and geometry, however. As the various phenomena governing hydrogen distribution are strongly coupled, large-scale global experiments have been conducted in addition to the analytical tests. A state-of-the-art report sponsored by OECD on containment thermal-hydraulics and hydrogen distribution was completed in 1999 by a group of international experts (including IRSN experts). It provides a description of all of the experiments (HEDL, HDR, BMC and NUPEC) conducted since the beginning of the 1980s. In most cases, they consist of large-scale global experiments using limited instrumentation and an imprecise knowledge of the boundary conditions, meaning that they can only be used to validate 0D computer codes and are unsuitable for validating multidimensional codes.

To overcome the lack of data, well-equipped new facilities were constructed at the beginning of the 2000s to validate the multidimensional, multi-compartment computational tools. These include the PANDA, THAI, TOSQAN and MISTRA facilities.

► PANDA facility programme

The PANDA facility at the Paul Scherrer Institute in Switzerland was initially designed for studying containment thermal-hydraulics in boiling-water reactors (BWRs). It consists of four interconnected compartments with a total volume of 460 m$^3$.

As part of the OECD SETH (SESAR Thermal-Hydraulics) project between 2004 and 2006, tests were conducted (mostly without condensation) on a test facility mainly

![Diagram of the PANDA facility.](image-url)
consisting of two compartments with a total volume of 180 m$^3$, using instrumentation specially designed to accurately measure the flows in order to validate the multidimensional codes. The test grid for this project concerned flows resulting from a lateral or central injection of steam or helium, gas jet interaction with the containment wall within the injection region, and the impact upon gas distribution of an opening between the two compartments in the upper part of the containment and those in its lower part. The PANDA facility offers the possibility of studying complex flows; the lack of control over the temperature of the facility walls prevents the condensation phenomenon from being precisely characterised, however.

More recently, a new experimental programme, OECD/SETHII [35], was conducted in the PANDA and MISTRA facilities to obtain additional data on transient flows under conditions that could result in the homogenisation of an initially-stratified environment. Various configurations covering the effect of hydrogen recombiner use and the spraying or injection of steam at different flow rates upon the elimination of previous hydrogen stratification were studied as a result.

► THAI programme

Becker Technology’s THAI facility in Germany is dedicated to analysing phenomena associated with the “hydrogen risk”, iodine chemistry, and the transport and deposition of aerosols in PWR containments.

Figure 5.20. Diagram of the THAI facility [36].
The 60 m$^3$ containment has a multi-compartmented internal structure with thermally-insulated external walls. With regard to the hydrogen risk, the THAI facility is designed for the study of hydrogen distribution and combustion, and the characterisation of catalytic recombiner operation. Between 1999 and 2002, the THAI facility was used to conduct thermal-hydraulics tests, one of which served as the basis of the OECD International Standard Problem (ISP) no. 47, which was completed in 2007 [18]. In this test, stratification of the gas mixture used (air, helium and steam) was created by injecting the helium and steam into the upper part of the containment (vertical injection); a lateral, low-flow-rate steam injection into its lower part could not cause movement throughout the compartmentalised containment atmosphere and so could not homogenise the gas mixture. This unexpected finding has shown the failings of the existing computer codes, which computed containment atmosphere homogenisation, and revealed the need to model flows in the injection regions in greater detail.

As a result, the study of phenomena governing the creation or destabilisation of stratification was continued as part of the OECD/THAI study [36] in order to improve the modelling of hydrogen distribution in a containment in the event of a core melt accident. As we will see later, the purpose of this project was also to study hydrogen combustion, recombiner behaviour and iodine chemistry. The tests conducted in this project also confirmed that the helium spread in the same way as hydrogen in the containment, meaning that it can be used in tests to study hydrogen distribution.

 ► TOSQAN programme

The TOSQAN facility, which IRSN has set up and operates at its Saclay site, consists of a cylindrical steel vessel with an internal volume of 7 m$^3$ (excluding the sump, the lower part of the containment containing water). The wall temperature of this containment is adjusted, allowing the cold area in which condensation occurs to be delimited. Instrumentation for the gas volume includes equipment for measuring its pressure, temperature, concentration of gas species (by mass spectrometry and spontaneous Raman scattering) and velocity (by laser velocimetry). The water droplets dispersed by the spray system are measured in terms of their size (using imaging), velocity (using laser velocimetry) and temperature (using refractometry). The test programme studies the phenomena of steam condensation, containment spray, condensation and evaporation at the interface between the sump and the containment atmosphere as well as the spraydown of aerosols by aspersion [26].

The condensation tests, one of which served as the basis of ISP47, have been completed; they studied the stabilised conditions (constant steam injection condensation flow rates) with and without helium. In the test on which ISP47 was based, the helium added to the steam injection began to spread homogeneously in the upper part of the facility (above the injection point). This is where the main convection loop is situated. Instability then develops as a result of the fluid heated by the walls in the containment lower areas, curtailing the slow helium enrichment phase there and causing movement throughout the atmosphere, homogenising the mixture as a result. Under steady-state conditions, the atmosphere is homogeneous.
Spraying tests with centred and off-centre spray nozzles have been conducted. In addition, an international comparative study has been organised on the basis of the tests conducted in the European SARNET network. Test campaigns have been also conducted to study the interactions between the containment atmosphere and the sump as well as aerosol spraydown, and their results have been analysed.

**MISTRA programme**

The main objective of the CEA MISTRA programme is to study condensation on the walls and on water droplets (from spraying) in a containment that is larger than that of TOSQAN and may contain compartments [27]. To be exact, the MISTRA facility consists of a 100 m$^3$ stainless-steel containment (diameter 4.25 m; height 7 m) that is thermally-insulated and has three temperature-controlled internal condensing surfaces. The instrumentation used includes equipment for measuring pressure, temperature, gas concentration and flow velocities (using laser Doppler anemometry). It can be used to qualify multi-compartment and multidimensional computer codes and their coupling.

The condensation tests conducted in the MISTRA facility, one of which served as the basis of ISP47, were carried out under stabilised conditions to reach a balance between the steam injection and condensation rates when steam is injected into the un compartmentalised or compartmentalised containment from centred and off-centre nozzles. In the test used for ISP47, in which helium was added to the steam injection flux, the helium distribution results were similar to those obtained in the TOSQAN test used for

![Diagram of the TOSQAN facility](image)
the same ISP. A homogeneous atmosphere was firstly created in the uniform part of the containment under the effect of convection currents; below the helium injection level, the helium concentration slowly increased until the containment atmosphere was completely homogenised in approximately three hours. The overall movement observed in the TOSQAN test described above did not occur because the lower part of the containment was colder than its other parts (in a stable configuration). The TOSQAN and MISTRA test programmes on spraying showed that it was effective in homogenising an initially-stratified gaseous atmosphere. The MISTRA containment is also used in the OECD/SETHII project to study the effect of low-velocity steam injection upon an initially-stratified atmosphere.

IRSN and CEA conducted a study of the effect of scale between the TOSQAN and MISTRA facilities in order to assess the possibility of using the existing computer codes for a PWR building. This study was based on tests for which the initial conditions and the limit conditions were similar, resulting in homogeneous mixtures. This work on
the heterogeneous gas mixtures is being continued in the European ERCOSAM project (2011–2015). In this project, the study involves tests defined using the results of severe accident scenario computations and conducted in the TOSQAN, MISTRA and PANDA facilities in Switzerland (see above) and SPOT and HYMIX facilities in Russia on volumes ranging between 7 and 1920 m$^3$; it will be used to assess the ability of the models developed and validated on the basis of small-scale tests to predict hydrogen distribution within a power reactor containment [33].

5.2.2.3.2. Hydrogen combustion

As for hydrogen distribution in the containment, many experimental programmes have been conducted on flame propagation in a premixed atmosphere containing hydrogen. These tests have two objectives: 1) to characterise the transition between slow and fast conditions and between deflagration and detonation; and 2) to produce a database for validating computer codes. There are two types of tests:

- analytical tests to determine the laminar flames’ characteristics and to construct a database for qualifying the different flame conditions;
- dedicated tests for studying turbulent flames with the aim of validating computer codes and establishing criteria for characterising the possible flame conditions.

As was the case for hydrogen distribution in the containment, a state-of-the-art report on flame acceleration and the deflagration-to-detonation transition was produced in 2000 by a group of international experts (including IRSN experts) within the framework of OECD [21]. This report provides a description of the major experiments conducted in the facilities of BMC, NUPEC, VIEW, HTCF, FLAME, RUT, etc. on flame acceleration and the deflagration-to-detonation transition. Criteria for the transition between the different combustion conditions were developed on the basis of the results obtained from the tests conducted in these facilities; these criteria were then refined as part of the European HYCOM programme and the ENACCEF programme (both these programmes are presented later in this document). It also reports on the state of the art in combustion models.

► RUT experimental programme

The RUT facility, which is operated by the Kurchatov Institute in Russia, has studied the turbulent combustion of hydrogen in a large-scale facility. IRSN and FzK (Germany) have helped to define and finance a set of tests in this facility. The facility, with a total volume of 480 m$^3$ and total length of 62 m, consists of three parts: one channel that is completely rectilinear, a second —shorter — channel that is curved at one end and a “canyon” or cavity in the intermediate area. All three regions have a rectangular cross-section and may possibly be blocked by obstacles.

These geometric characteristics can be used to study both the mono-directional acceleration of a flame produced as a result of hydrogen combustion in the channels and more complex 3D effects or interactions in the “canyon”. It is the only facility of its size used to study turbulent hydrogen combustion and thus the only one subjected to
pressure loads that can be transposed to reactor scenarios. The gas mixtures used in the tests, which contained hydrogen, air and possibly steam, are supposed to be representative of the mixtures present in a containment when a core melt accident occurs. The instrumentation is highly suitable for validating CFD computer codes [22].

The various test campaigns have investigated the following combustion conditions:

- slow deflagration, in which flame velocities are below the speed of sound in the case of cool gases and the pressure levels are below the adiabatic isochoric complete combustion (AICC) pressure;

- fast deflagration, in which flame velocities are around the speed of sound in the case of burnt gases and the pressure levels are above the AICC pressure;

- “critical” conditions, in which a deflagration-to-detonation transition (DDT) occurs but the resulting detonation does not spread or is not directly transmitted to the entire mixture;

- stable detonation, in which the detonation forms after a DDT in one region of the facility and in which the velocities and pressure peaks are close to the Chapman-Jouguet values (CJ) and propagate to the rest of the fuel mixture.

The objectives of the different programmes conducted in the RUT facility have included the establishment and validation of the criteria $\sigma$ and $\lambda$ (defined in Section 5.2.2.2).

► HYCOM European programme

 The European HYCOM programme has been designed to build upon the first tests conducted in the Kurchatov Institute RUT facility in the context of a collaboration between FzK, the US NRC, IRSN and the Kurchatov Institute; its objective is to study flame acceleration in hydrogen-air mixtures and especially to validate the $\sigma$ criterion [25]. The effect of burnt gas expansion (the “piston” effect) and the impact of compartmentalisation were studied using the RUT facility; the impact of venting was studied using the DRIVER and TORPEDO facilities operated by FzK, consisting of cylindrical tubes that are 174 mm in diameter and 12.2 m long and 520 mm in diameter and 12.4 m long, respectively.

This programme, in which IRSN and EDF participated, also added to the available data on flame acceleration and validated the criteria for special situations in which there are gas mixture richness and containment geometry differences.
The ENACCEF (flame acceleration containment) programme on flame acceleration was conducted for IRSN by CNRS and, during its initial years, EDF. Its primary goal was to validate the criterion $\sigma$ using tests conducted on a vertical structure representing an SG bunker opening up into the dome [17]. The ENACCEF facility contains an acceleration tube forming the lower part of the containment and an adjustable dome forming the upper part of the containment. The acceleration tube, which was 168.3 mm in diameter and 3.2 m high, can be fitted with obstacles of various shapes, resulting in different blockage rates and notably an obstacle simulating an 11.12-litre SG. The adjustable dome volume may be 780.9 litres or 957.8 litres.

The instrumentation used includes photomultiplier and pressure sensors for measuring the progression of the flame front and the pressure generated as a result of hydrogen combustion. In addition, gas sampling points are positioned along the facility’s acceleration tube to measure the composition of the gas mixture within the facility. Lastly, laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) are used to determine the velocity field of the gas flow before the combustion flame reaches it. The ENACCEF facility is therefore well equipped with instrumentation and particularly well suited to validating CFD computer codes. It can also be used to study the flames’ upward and
downward propagation, taking into account the ignition points at the bottom and top of the facility. The effects of dilution by steam simulant gases and of the volume and heterogeneity of the mixture have been studied in addition to those of the ignition position; this has confirmed and improved the criterion $\sigma$ developed in the RUT and HYCOM programmes as well as obtaining data for the validation of CFD computer codes. The ENACCEF facility has also studied the effect upon flame propagation of the presence of water droplets due to spraying. These results showed that under certain conditions, the flames progressed more rapidly when the spray system was activated. This statement had been confirmed by the experiments results performed in framework of the OECD/THAI II project (2011–2014).

Some tests were also conducted in the ENACCEF facility and served as the basis for the international comparative exercises organised within the European SARNET network and the OECD International Standard Problem no. 49 [34].

5.2.2.3.3. Means of reducing the hydrogen risk

Catalytic hydrogen recombiners (see Figure 5.26) have been set up in the French PWRs' containments to reduce their hydrogen content in the event of a core melt accident. They are usually constructed from a catalytic material (platinum or palladium on an alumina mounting) and housed in a metallic casing whose purpose is to enable the gases to circulate inside the catalyser (consisting of a bed of beads or a row of vertical plates). On contact with the catalytic recombiner plates, the hydrogen and oxygen present in the containment atmosphere react to produce steam.

Many test programmes, most of which were conducted by the recombiners' manufacturers (SIEMENS, AECL, etc.) [20], have studied the behaviour of the recombiners in the event of a core melt accident in order to evaluate their recombinatory capacity.

The H2PAR programme, conducted by IRSN at its Cadarache facilities with financial support from EDF, was mainly intended to investigate the behaviour of the catalytic hydrogen recombiners [19] in an atmosphere representative of that found in the

![Figure 5.26. Block diagram of a passive catalytic hydrogen recombiner.](image-url)
Development of the core melt accident

containment in the event of severe accident within chemical compounds in aerosol form (creating a risk of catalyser poisoning). It also studied the risk of the mixture present in the containment igniting as a result of the recombiner (which heats up in the recombination reactions) and determined the limits above which such ignition would occur for a given recombination model. In addition, it analysed recombination sensitivity to different geometric parameters (number of catalytic recombiner plates and height of the passage between the plates (called the “stack”), physical parameters (molar fraction of hydrogen) and chemical parameters (replacing several catalytic plates by chemically neutral plates) [29]. These tests notably demonstrated the aerosols’ limited impact upon recombination efficiency.

The aims of the KALIH2 test programme, conducted by CEA with financial support from EDF, were complementary to those of the H2PAR programme and concerned the behaviour of the recombiners in special situations (when not poisoned by the fission products). It evaluated the effects of the following upon recombiner

Figure 5.27. Picture of the REKO 4 facility (credit: Jülich Institute).
performance: humidity, exposure to smoke from cable fires, and the presence of carbon monoxide [23, 24]. Unlike H2PAR, KALIH2 studied the impact of spray system use and overpressure upon recombiner efficiency. The tests revealed that spray system use has little effect recombiner efficiency but overpressure has a major effect upon it.

More recently, the OECD/THAI project confirmed and supplemented the H2PAR and KALIH2 programmes’ results concerning the limits of ignition by the hydrogen recombiners and their performance under conditions in which there is little oxygen.

The effect of the hot plumes emitted from the recombiners upon hydrogen distribution in the containment, which the H2PAR and KALIH2 programmes did not address, was also studied in the OECD/SETHII programme tests as well as in additional tests as part of the European ERCOSAM project, in which recombiner models were used in the PANDA, MISTRA and KMS facilities. It is also being studied in the European SARNET project by conducting tests with recombiners in the REKO 4 facility operated by the Jülich Institute.

5.2.2.4. Modelling and simulation codes

The computer codes used to predict hydrogen distribution in the containment are based on a multi-compartmental approach. These include the CONTAIN, MAAP, GOTHIC, MELCOR and COCOSYS codes, the ASTEC code CPA module and the TONUS code multi-compartment computation module. These codes have demonstrated their ability to compute hydrogen distribution in small- and large-scale experiments, with or without the use of a spray system. The models used by these codes are too simple to precisely describe the complex gas flows likely to be produced locally at the power reactor scale, notably in the volumes in which concentration differences can appear (stratification, jets, etc.).

The codes that use a multidimensional approach, such as the TONUS code multidimensional module or the GASFLOW code developed by KIT, can model complex flows much more precisely and so can be used to complete the studies conducted using the codes listed above in the case of complex flows. They may be of limited use in some cases, however, due to the geometric complexity of the internal structures of the containment as well as to the costs involved, which may be considerable.

The comparative computational exercises (ECORA and ISP47) based on the experimental results of the four programmes named above have led to the following conclusions.

The ECORA exercise, which involved a gas injection transient with no steam condensation, used CFD tools and showed that the main limitation in the use of this type of computer code lay in the computation of large-scale slow transients. The existing means of computation are not powerful enough to allow computation convergence or mesh sensitivity over time to be studied. The models used have accurately predicted steam transport between the compartments of the PANDA facility, however, which was one of the key points of this exercise.
In the ISP47 exercise, multi-compartment and multidimensional computer codes were used. Furthermore, as several research bodies have used the same tool, it has been possible to assess the user effect more accurately. The following points were emphasised in the final conclusions of the exercise:

- the CFD tools have not shown any significant advantages over the multi-compartment tools, possibly due to the relatively simple flow structures in the case of the TOSQAN and MISTRA tests;

- the results obtained using multi-compartment tools varied greatly depending on the user. They have therefore highlighted the need to draw up and implement best practices (this recommendation is also true of the CFD codes that use the correlations);

- the “blind” exercises, which are important in assessing the codes’ predictive aspect, produced a wide range of results;

- supplementary studies are needed in order to model the condensation of steam on the walls, notably concerning the effect of the presence of helium;

- the processing of the effects of scale in computer codes has not been fully resolved: this is the objective of the European ERCOSAM project.

Additionally, the pressure loads resulting from hydrogen combustion and applied to the containment can be computed using codes adopting multi-compartment or multidimensional approaches. The multi-compartment codes are generally used to compute slow flames whose pressure loads can be considered as being static. Multidimensional CFD codes must usually be used to compute the dynamic pressure loads, however. For example, the HYCOM project has produced very complete results with regard to hydrogen combustion in reactor containments and the modelling of this phenomenon. In particular, this project has revealed the following:

- global values such as the maximum pressure are relatively well-computed by the CFD and multi-compartment codes. CFD codes give better results for fast flames, however, whereas multi-compartment codes are better suited to slow flames;

- differences exist between the results obtained using the various codes for “dynamic” values, such as the flame velocity or pressure build-up;

- the computer codes do not accurately compute some experimentally-observed phenomena such as smothering;

- modelling the energy dissipation of the flame during its progression is an important point and must be improved.

Above all, however, the HYCOM project has highlighted the difficulties of modelling hydrogen combustion when the mixtures are not homogeneous, particularly when this is accompanied by a change in the combustion conditions. These situations — which are nevertheless similar to actual conditions — are not modelled satisfactorily and require additional experimental data, notably concerning the turbulence level, to allow the computer codes to be validated. This was also the finding of the comparative exercises.
applying the codes to the OECD *International Standard Problem* (ISP49) and in the SARNET project.

### 5.2.2.5. Summary and outlook

Research and development on the hydrogen risk have produced a number of results reinforcing the decision to install passive hydrogen recombiners in all French nuclear power plants. Studies of core melt accident scenarios in the case of the existing reactors and the EPR have shown that despite the installation of recombiners, it is difficult to prevent, at all times and locations, the formation of a combustible mixture potentially resulting in local flame acceleration.

Furthermore, the events that occurred at the *Fukushima Daiichi* nuclear power plant in Japan have shown that the R&D studies must be continued in order to advance the state of knowledge of hydrogen risk phenomena.

Additional research is being conducted to improve the tools needed to evaluate the hydrogen risk. This concerns the following:

- in the case of hydrogen distribution, studies of transient flows with stratification. This aspect was studied in the SETHII project and is now being studied in the test programmes of the European ERCOSAM project, notably in the TOSQAN, PANDA and MISTRA facilities;

- in the case of combustion, studies of the effect of the presence of water droplets upon hydrogen flame acceleration. This subject is covered in the ENACCEF programme and is part of the current OECD/THAI II project;

- in the case of recombiners, studies of how the recombiners’ location affects the recombination rate as well as flame ignition by the recombiners. Both these subjects are covered in the European SARNET network and are being studied in a programme based on the tests conducted in the REKO3 and REKO4 facilities. The effects of the recombiners’ location upon the surrounding atmosphere are also discussed in the OECD/SETHII project;

- in the case of hydrogen distribution, the development of models representing steam condensation in the presence of incondensable gases and stratification, as well as “destratification” mechanisms. Furthermore, the comparative exercise organised by IRSN regarding spraying have shown the limits of the computer codes in describing the effect of spraying upon atmospheric mixture kinetics;

- in the case of hydrogen combustion, additional work to improve and validate the models is needed in order to better simulate flame propagation in a heterogeneous environment, notably when there are differences in the hydrogen concentrations enabling the flame propagation condition to change.

In conclusion, the R&D conducted to date has significantly increased our knowledge of the phenomena governing the distribution of gas mixtures and their combustion in the containment when a core melt accident occurs. In particular, by enabling us
to establish criteria that have been validated using experimental data, it has enabled us to more accurately determine which situations involve hydrogen combustion risks. Although the computer codes have now achieved a significant level of maturity, their predictive capabilities must be further improved by defining best practice guidelines to mitigate the "user" effect, by improving the models (notably regarding combustion), or else by improving the numerical performance of the CFD multidimensional tools and increasing the computing power of the computers permitting their widespread use.

5.2.3. **Steam explosions**

5.2.3.1. **Introduction**

The phenomenon of steam explosions is relatively well understood since the 1970s. When two fluids come into contact, with one (the molten fuel, or corium, resulting from core meltdown) being at a temperature higher than the boiling point of the other (the coolant), an explosive interaction may be caused. This phenomenon is the result of the chained interaction of several mechanisms shown below:

Corium fragmentation into ultra-fine fragments below a hundred microns in diameter causes the transfer of energy from the corium fragments into the coolant. The associated phase change (or simply density changes) may induce a pressure build-up faster than the pressure release. The pressure build-up causes relative motion in the fluids (the water moves faster than the fuel because their densities are different). This leads to substantial overpressure, followed by a more or less slow expansion that may damage surrounding structures (overpressures of up to 1000 bar have been measured in the KROTOS tests conducted in the Joint Research Centre (JRC) at Ispra in Italy, using alumina as a simulant of corium. Two additional phenomena have significant impacts. The heat transfer induces a cooling of the melt and thus its solidification, which, to a degree to be specified, will prevent the fragmentation. Experiments have also shown that oxidation may be very intense. Through the associated energy and through the
production of hydrogen, a non-condensable gas, oxidation has strong impacts which may either limit or enhance the explosion strength.

The prerequisite condition for triggering a steam explosion is the contact between the two fluids, but the situations generating most energy are those in which the two fluids are mixed before they are finely fragmented (hence the terms “pre-mix” or “pre-mixing”). In the case of PWR or BWR core melt accidents, such mixtures may form after core meltdown and while the corium is flowing in the lower head if any water remains (“in-vessel” explosion), and then possibly in the flooded reactor pit when the vessel is penetrated (“ex-vessel” explosion).

This condition is not sufficient in itself, however: an explosion does not necessarily occur when the fluids are in contact or mixed. The corium then remains at the coarse fragmentation stage (with fragments millimetres or centimetres in diameter) and its energy is transferred to the coolant relatively slowly (approximately a second for one droplet), resulting in the pressure slowly building up (this is what occurred in the Three Mile Island-2 accident, described in Section 7.1). In order for an explosion to occur, there must be an “internal” triggering event (producing what is referred to as a spontaneous explosion) or an “external” event (shock wave), causing fine fragmentation somewhere in the pre-mix and then propagating throughout the rest of the pre-mix. Such spontaneous or artificially-triggered explosions have been experimentally produced with the molten materials of which a PWR corium is composed (a mainly U–O–Zr–Fe mixture).

In its most extreme form, a steam explosion is similar to a detonation due to a chemical reaction, with a shock wave propagating at the speed of sound and heat transfers between the fragmented corium and the water playing an equivalent role to the release of energy in chemical reactions. The analogy is somewhat limited, however, and quite unrealistic approximations are needed in order to construct analytical models (based on detonation models), which have very little potential for practical application. This is why complex multiphase and multidimensional models are needed in order to compute steam explosions. The most frequently-used computer code in France is the MC3D code developed by IRSN in collaboration with CEA (Section 5.2.3.3.3).

The OECD SERENA (Steam Explosion RESolution for Nuclear Applications) programme brought together the leading steam explosion specialists. In its initial phase between 2001 and 2005, they evaluated the current state of knowledge of the phenomenon and assessed the computational capabilities of the main dedicated software solutions [44]. The second phase of the programme, which took place between 2008 and 2012, consisted of an experimental programme devoted to studying steam explosions with various corium compositions likely to be found in a power reactor core melt accident, with the aim of improving the existing models (Section 5.2.3.3.2).

5.2.3.2. Physical phenomena

While the corium melt is in the water present in the lower head or, after the vessel ruptures, in the reactor pit, the explosive interaction appears as a two-stage dispersion and fragmentation phenomenon shown diagrammatically in Figure 5.28. The first
stage — the pre-mixing phase — may, depending on how it occurs, result in the explosion itself (the second stage) due to the fundamental, self-sustaining mechanisms described in the introduction: fine corium fragmentation, energy transfer between the fragmented corium and the water, and the associated pressure build-up and differentiated motion in the fluids. As the pre-mixing and explosion phases’ timescales are very different (seconds compared with milliseconds), the explosion takes place within a virtually static pre-mix that determines the initial conditions of the explosion.

As a result, the explosion greatly depends on the pre-mix characteristics at that time; these consist of the composition and distribution of the various phases present (corium, water and steam) and the corium interface, including its temperature and its possible state of solidification. It is thus essential to accurately describe this first phase in order to obtain the initial conditions of the explosion. Accurate prediction of the explosion phase is therefore achievable only if pre-mixing is accurately described. This first phase was neglected for some time but has been the subject of most R&D efforts for the last ten years.

The explosion therefore begins with a “trigger” phase and is followed by a phase referred to as the “escalation” phase, during which the intensity of the explosion increases until a stationary state is reached. There is no phenomenological difference between these two steps of the explosion and they are modelled in the same way in the current computer tools. On the following pages, we will use the more general term “explosion phase” to describe them both. The pre-mixing, the triggering of the explosion and the explosion itself are described in detail in the following sections.

5.2.3.2.1. Pre-mixing

The importance of pre-mixing has been clearly demonstrated, particularly in the KROTOS experiments, in which the very different pre-mixes observed with the alumina and the corium (Figure 5.29) resulted in very different explosion intensities (alumina
releases ten times more energy than corium) [37]. In all the tests, mostly qualitative information was obtained on the pre-mixing of materials with high melting points (> 2000 °C). This information is not sufficient to explain the observed differences in behaviour. The second phase of the OECD/SERENA programme sought more detailed information on the pre-mixing, notably concerning the fragmentation and boiling processes (Section 5.2.3.3.2).

With regard to modelling, pre-mixing is evaluated using multidimensional, multiphase thermal-hydraulic computer codes (Section 5.2.3.3.3), as the many dynamic, thermal and chemical interactions prevent pre-mixing from being modelled simply.

The three essential points upon which R&D concentrates, namely corium fragmentation, determining of the void fraction (the fraction of the volume occupied by the steam) and fuel solidification, are presented below. For the sake of completeness, the effects of oxidation of the corium materials — which could greatly modify each of these points — should also be studied.

**Corium fragmentation**

During the pre-mixing phase, fragmentation occurs in two stages: primary fragmentation, from the continuous phase (typically a corium jet), produces a first generation of droplets that may then undergo secondary fragmentation. In reality, jet fragmentation is a highly complex phenomenon and involves several instability and then fragmentation processes, as Figure 5.30 shows.

Secondary fragmentation continues until the droplets formed cannot become any smaller (the droplets consist of fragments wrenched from larger droplets by the gas flow; this fragmentation is only possible if the droplet is unstable under hydrodynamic flow conditions).
Considerable research has been conducted on the primary fragmentation of corium jets (in particular, see the results of the doctoral theses presented in references [42, 43]). The models developed in these theses are mainly devoted to direct fine fragmentation (atomisation) of the corium jet. It was, however, seen that the corium jet can be fragmented by other mechanisms involving “large-scale” hydrodynamic instabilities causing larger fragments to be formed and greater spatial dispersion of the corium fragments (Figure 5.31). These mechanisms are believed to cause the behaviour observed during tests with alumina in the KROTOS facility [37], where the fragments filled the entire cross-section of the experimental tube (see Figure 5.29).

Secondary fragmentation was the subject of substantial work until the 1980s. This work revealed trends and fundamental characteristics numbers (Weber number: $We = \frac{\rho_{amb} V^2 D}{\sigma}$; characteristic fragmentation time: $\frac{D}{V} \sqrt{\frac{\rho_{comb}}{\rho_{amb}}}$). The knowledge acquired as a result only provides a qualitative description of the pre-mixing, however.

Apart from the fact that the theoretical knowledge must be improved, the modelling of fragmentation in the computer codes faces two difficulties. The first concerns the local aspect of the phenomena, resulting in the need for fine spatial resolution, whereas the second lies in the models’ extreme sensitivity to the local flow conditions, which are quite unstable and can trigger the explosion themselves. Parametric modelling of flow dynamics is therefore often preferred to more-detailed modelling; this approach, which is based on simplified models of the gravitational fall of corium fragments, is of limited use, however, as these simplified models have not been sufficiently validated to compute corium–water pre-mixes when a core melt accident occurs in a power reactor.

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7. This must not be confused with the “fine fragmentation” process during the explosion, in which the fragments are much smaller.
Void production

The volumetric fraction of the gases in the corium–water mixture is called the “void fraction”. There are still many uncertainties regarding the effect of the void fraction upon steam explosion, however. The greater the void fraction is, the more the average compressibility of the mixture increases and the more explosion becomes difficult. Predicting the void fraction in the pre-mix (the initial state of the explosion) is a complex task, mainly because of the corium’s very high temperatures (it should be remembered that at 3000 K, the steam is already greatly dissociated). The steam production processes of film boiling are poorly understood. Similarly, the steam condensation processes are very difficult to model. The flow configurations used in modelling are based on studies of isothermal two-phase flows in piping. Their suitability for describing pre-mixing is therefore uncertain. The presence of non-condensing gases produced through oxidation of corium metallic phases modifies the boiling and condensation processes, making the void fraction even more complex to model.

This results in a certain degree of disparity between the existing models, and this disparity is largely the cause of the uneven computational results obtained during phase 1 of the SERENA programme. Due to the lack of detailed experimental results, particularly concerning the local void fractions and the corium’s configuration, the validity of the various models cannot be established with sufficient certainty. Correctly evaluating the void fractions and their distribution was thus a major objective of phase 2 of the SERENA programme, as described in Section 5.2.3.3.2.
Corium solidification

An additional phenomenon must be taken into account when the models are applied to power reactors. This concerns corium solidification during the pre-mixing phase, which inhibits the fine fragmentation process and, therefore, the explosion. This phenomenon is particularly difficult to study because of the complex mixtures of component materials in corium and the complex pre-mixing conditions (gas and corium flows, corium fragmentation, high temperatures, etc.). As a result, considerable uncertainties remain regarding the solidification processes themselves. The codes computing these processes (including MC3D) assume that solidification occurs under thermodynamically balanced conditions, and that there is a solid surface crust and a well-defined solidification front.

5.2.3.2.2. Triggering of the explosion

The steam explosion triggering phase is undoubtedly the most difficult phase to process when evaluating the steam explosion risk. There are no reliable models for predicting when and where an explosion will be triggered. The physical parameters that determine the triggering of the explosion are not precisely known. The existing knowledge is mainly based on experimental results. In the case of corium, it has been experimentally observed that spontaneous explosions occur when the corium makes contact with the test system lower head containing the corium-water mixture. However, nothing says that an explosion could not occur before or after this contact.

From a theoretical point of view, it is known that a hot corium droplet may explode under the influence of a low-pressure disturbance of a few bar (Figure 5.32). The phenomenon includes isotropic fragmentation, unlike the fragmentation linked with dynamic effects (the fragments are found in the flow’s wake). Despite many research studies, this “thermal fragmentation” phenomenon is still poorly understood. However, a doctoral thesis study conducted from 2005 to 2008 at IRSN [45] added to our understanding of this phenomenon and validated the most widely-poseded hypothesis whereby the phenomenon is due to the steam film surrounding the corium droplet becoming destabilised. This destabilisation causes localised contact between the corium and the coolant, thereby creating local build-ups in pressure that, in their turn, destabilise the corium droplet. The corium’s “thermal fragmentation” phenomenon only appears possible under fairly specific conditions of ambient pressure (approximately 2–15 bar) and water under-cooling (above 70 °C according to the experimental results obtained by the Sandia National Laboratories [64], and above 40 °C according to the model in this doctoral thesis). It is thought to contribute to the triggering and escalation of the explosion, but its actual importance has not yet been determined. A spontaneous explosion was therefore observed at a pressure of 50 bar in a programme at the British Winfrith nuclear centre under apparently unfavourable conditions for thermal fragmentation [38].

An explosion may also be triggered by the corium enveloping some coolant when it lands on the floor (the bottom of the testing cross-section), which would explain the spontaneous explosions occurring when the corium comes into contact with the floor. Furthermore, the small scales of the tests do not encourage spontaneous explosions.
Spontaneous explosions therefore occur more frequently in the experiments conducted with wide testing cross-sections (the FITS \([32-34]\) or TROI \([62]\) programmes) than in geometries with narrow cross-sections (KROTOS \([37]\)).

In the probabilistic safety assessments, a triggering probability is sometimes used. No probabilistic quantification is currently based on precise physical arguments, however. Uncertainties regarding the triggering of the explosion therefore lead us to consider that steam explosion risk cannot be eliminated and to study the consequences of such an explosion. It should be noted, however, that the triggering caused by a pressure disturbance does not necessarily result in an interaction likely to endanger the structures if the temperature and pressure conditions are not combined. In the computations as well as in some experiments, therefore, certain situations that notably have a high void fraction or high solidification do not result in an explosion that threatens the structures (or any explosion whatsoever).

5.2.3.2.3. Explosion

The explosion is caused by very intense heat transfers between the corium and the coolant and the resulting coolant vaporisation\(^8\). In the case of the violent explosions such as those obtained in the KROTOS facility’s mono-dimensional geometry using

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\(^8\) It may seem surprising to speak of vaporisation when the pressure exceeds the critical pressure. In this case, we are misusing the term to describe the fact that, even under supercritical conditions, the hot fluids are still less dense than the cold fluids, a phenomenon similar to evaporation.
alumina (with pressure peaks of 500–1000 bar), the explosion may be approximately described as follows:

- propagation of a detonation-type shock wave with intense isochoric thermal transfers;
- expansion of the mixing region behind the passing shock wave.

Because of the obvious instrumentation limitations, experimental studies on the detailed mechanisms of the explosion are extremely complicated. As a result, very little data — which have often been obtained under questionably representative conditions — are available. The analytical models, concerning complex phenomena that are frequently unbalanced, reach their limits comparatively rapidly. It is, however, interesting to note that with the increase in computing power, it is becoming feasible to study these highly localised phenomena using numerical simulation tools (such as the MC3D code itself, described later in this document).

Paradoxically, however, the explosion is comparatively “simpler” to model than the pre-mixing phase, subject to the use of suitable approximations for the corium’s fine fragmentation as well as heat and mass transfers between the corium and the coolant, as these processes produce the pressure peak. For one thing, these two processes are clearly predominant mechanisms; for another, many aspects can be simplified or even ignored because of the timescale of the explosion (a few milliseconds). The studies therefore concentrate on understanding the two predominant phenomena, consisting of the fine fragmentation of the corium and the boiling of the coolant, both of which are briefly described below.

▶ Fine fragmentation

The fragmentation mechanisms are astonishingly complex (see, for example, reference [66]). The fine fragmentation of a corium droplet in water when subjected to a shock wave is illustrated in Figure 5.33, from reference [46]. Traditionally, the fragmentation phenomena are characterised by means of the Weber number \( \text{We} = \left( \frac{\rho V^2 D}{\sigma} \right) \), which expresses the ratio between the destabilising dynamic forces \( (\rho V^2) \) and the stabilising force due to surface tension \( (\sigma/D) \). When the Weber number is not too large, the droplet surface layers are firstly detached due to water friction. The fragmentation occurs later behind the film drained by the friction. With high Weber numbers, instability occurs earlier and directly results in droplet fragmentation.

When the corium is finely fragmented, the size of the droplets is reduced by one or two orders of size in approximately one millisecond. Opinions differ regarding the way in which the phenomenon develops. The studies conducted by IRSN using the MC3D computer code suggest that the corium’s fine fragmentation is the result of Kelvin-Helmholtz shearing instabilities (because the flow speeds of the corium and coolant droplets are different). These studies have led to the development of a model describing the changes in the fragments’ size; this model is integrated into the MC3D code.
Corium solidification tends of course to modify or even inhibit the phenomenon, potentially explaining the (relative) weakness of the explosions observed with corium oxide (UO$_2$ + ZrO$_2$). It is difficult to model the solidification phenomenon during the premixing phase, however. This is because its effect upon fine fragmentation is difficult to quantify. In some models, the crust has an effect similar to an elastic shell. The models remain highly parametric, however, due to the many approximations and uncertainties concerning, for example, the mechanical properties of the solid corium layers.

**Pressurisation mechanisms**

The initial steam explosion models [47] assumed that there was an instantaneous balance between the resulting corium fragments and the coolant; in these models, the coolant temperature increase due to direct contact with the hot corium fragments directly results in the pressure build-up, either through boiling or simply through thermal expansion. This approach has been refined by Theofanous [48] with the so-called “micro-interaction” approach, which considers that only a fraction of the water is heated. The term “micro-interaction” comes the hypothesis that the interaction between the fragment and the water is highly local and that only a part of the water is involved (except in transmitting the pressure build-up). Experimental observations show that in reality, at least up to the critical pressure, the hot corium fragments are surrounded by a thin film of steam, affecting the heat transfers between the corium fragments and the coolant as well as coolant vaporisation. The model representing the interaction between the corium fragments and the water integrated into the MC3D code assumes that the pressure build-up is the result of the direct vaporisation accompanying the heat transfers through the steam film between the hot corium fragments and the coolant (the so-called “imbalance” model); this model, which is more mechanistic *a priori*, assumes that the mass...
transfers associated with the heat transfers between corium fragments (whose average size is 100 µm in the KROTOS experiments) and the coolant are known. It is important to remember that these transfers occur during a pressure transient of a few hundred bar lasting a few milliseconds, which are difficult conditions to achieve in experiments.

5.2.3.3. Experimental programmes, modelling and computer code

5.2.3.3.1. Mechanical efficiency concept

Before we present the main experimental programmes, it is important to discuss the mechanical efficiency concept, as it is often used to characterise the intensity of an explosion in the experiments (as well as in the initial thermodynamic models). This concept is intended to represent the efficiency of the transfer of the heat energy contained in the fuel, the source of the explosion’s energy (excluding chemical phenomena), into mechanical energy. In reality, this concept is rather vague, as the mechanical energy concerned can be defined in several ways. In the initial estimates, the energy in question was that linked with the system’s overall pressure build-up — in other words, the gaseous atmosphere in the test section (the compression is assumed to be adiabatic). In reality, this definition created considerable difficulties and expression used for the energy was revised several times. It was then judged preferable to use the kinetic energy of the mixture. To avoid confusion, we will talk of kinetic efficiency in the rest of this document. This kinetic energy is also impossible to measure accurately, and it is generally obtained by evaluating load impulsion (the pressure build-up integral, \( I = \int S \Delta P \, dt \), where \( S \) is the bottom surface area of the test cross-section to which the pressure load \( \Delta P \) is applied). Although the mixture is assumed to be non-deformable (like a slug) and expelled by the explosion, the approximate value of its kinetic energy is provided by the expression \( I^2/2M \), where \( M \) is the mass of the mixture. This approximation leads to a minimisation of the actual energy but provides acceptable orders of magnitude.

The efficiency concept must therefore be used with caution, and any comparisons between different experiments must be purely qualitative.

5.2.3.3.2. Experimental programmes

Table 5.4 shows the main programmes that have studied the pre-mixing phase or the steam explosion using corium or simulant jets and whose results have been used as the basis for developing and qualifying computational models. The FITS programme, which was the “pioneer” in the domain, was conducted by the Sandia laboratories in the United States and included many experiments in the different configurations and on different materials described in references [38-41]. Notably, spontaneous violent explosions were obtained using a corium consisting of a \( \text{UO}_2 + \text{ZrO}_2 \)-steel mixture (little information is provided on the corresponding tests, unfortunately) [49]. The programme ended with the loop being unexpectedly destroyed in the RC2 test. These experiments are not used to qualify the codes, however, as little is known of the experimental conditions under which the fluids come into contact, and so the conditions are often poorly known and difficult to reproduce in the computations.
Table 5.4. Experimental programmes studying steam explosions resulting from an interaction between a corium jet or a simulant jet and the coolant (water).

<table>
<thead>
<tr>
<th>Programme</th>
<th>Laboratory</th>
<th>Type of test</th>
<th>Materials</th>
<th>Conditions and key facts</th>
</tr>
</thead>
</table>
| FITS      | Sandia (USA)| Explosion    | Al₂O₃-Fe thermite or corium A few kg | - First major programme  
- Many tests  
- Series of extended conditions  
  materials (MDC) tests with corium: spontaneous explosions (approx. 2% efficiency)  
- Series of extended efficiency (RC) with thermite: RC2 experiment with the highest observed efficiency (8–15%, gas compression work) |
| CCM       | ANL (USA)  | Pre-mixing   | UO₂ + ZrO₂- steel mixtures at 2800 °C A few kg | - Well-controlled conditions  
- 6 tests under different conditions (including geometry, jet diameters and water temperature)  
- No spontaneous explosions |
| FARO      | CCR Ispra (European Commission) | Pre-mixing  
Explosion | UO₂ + ZrO₂ at 2800 °C 100–200 kg | - Very large programme  
- Reference for pre-mixing phase model qualification  
- Large masses  
- No spontaneous explosions  
- Explosion test with trigger (low efficiency) |
| KROTOS    | CCR Ispra (European Commission) | Explosion | Sn at 1000 °C Al₂O₃ at 2300–2800 °C  
UO₂, ZrO₂ at 2800 °C 1 litre | - Reference programme for explosion code validation  
- One-dimensional (narrow test cross-section)  
- Influence of the composition (alumina or corium UO₂ + ZrO₂)  
- No spontaneous explosions with corium |
| ZrEX-ZrSS | Sandia (USA) | Explosion    | Zr + ZrO₂ mixtures Zr–steel A few kg | - Triggered explosions  
- Very great impact of Zr rate upon efficiency |
| TROI      | KAERI (South Korea) | Explosion  
+ Pre-mixing | UO₂ + ZrO₂ corium Around 10 kg | - Poorly defined conditions  
- Spontaneous explosions  
- Low efficiency  
- Only 2 kg in the mixture at the time of explosion  
- Influence of corium composition |

The reference results regarding the pre-mixing phase are based on the FARO experiments (conducted by the European Commission Joint Research Centre (JRC) at Ispra in Italy) [54], which used 100–200 kg of corium oxide (UO₂ + ZrO₂). The KROTOS
Development of the core melt accident programme (which was also conducted at the JRC in Ispra) \[37\] was similar to the FARO programme in studying the explosion, albeit at a smaller scale (fuel volume was approximately one litre); this programme demonstrated a lower tendency towards explosion as well as lower pressure loads for a corium oxide (\(\text{UO}_2 + \text{ZrO}_2\)) in comparison with alumina (\(\text{Al}_2\text{O}_3\)). This result was the subject of considerable speculation regarding the “material effect”. The difference in density between the corium oxide and the alumina may explain this result; the lower density of the alumina has two effects: firstly, jet fragmentation into larger particles, resulting in less vaporisation and solidification, and secondly, an increase in the volume of fuel in the mixture because the speed of deposition on the bottom of the test cross-section is lower. The kinetic efficiencies (Section 5.2.3.3.1) of the strongest explosions were evaluated at approximately 2%, which is similar to those of the explosions in the FITS programme.

We should also mention the programmes whose results are little used, either because of a specific complication in the results or because of limitations in the dissemination of the results. The former category notably includes the ZREX tests by the Argonne National Laboratory in the United States \[50\], which revealed that explosion intensity was very greatly increased due to oxidation of the zirconium contained in the \(\text{Zr} + \text{ZrO}_2\) and Zr-steel mixtures.

The TROI programme, which was conducted by the Korea Atomic Energy Research Institute (KAERI) in South Korea, confirmed that spontaneous explosions were possible with corium \[56\].

To support modelling, experimental programmes investigating separate effects (thermal transfers, fragmentation, etc.) have been conducted, generally in a national context. Notably, the TREPAM tests (CEA/IRSN) have made it possible to specify the heat transfers associated with the corium fragments under fairly representative conditions (pressures of up to 240 bar, speed differences between fragments and water of up to 46 m/s and temperatures of approximately 2200 °C). In the case of fine fragmentation, the DROPS programmes (conducted at the Institut für Kernenergetik und Energiesysteme (IKE) in Stuttgart, Germany, and then at CEA) \[50\] and MISTEE (conducted at the Royal Institute of Technology (KTH) in Stockholm, Sweden) \[61\] were devoted to studying the fragmentation of the corium droplets in the water by using simulants (generally liquid metals) at relatively low temperatures.

In order to validate the codes, various programmes also tried to represent the corium jets by jets of solid beads, thereby eliminating the fragmentation-related difficulties in order to concentrate on the heat transfer and friction aspects. In particular, the QUEOS programme conducted by Forschungszentrum Karlsruhe in Germany \[51\] studied the pre-mixing phase of solid sphere packets for temperatures of up to 2200 °C.

At the end of the programmes described above, many uncertainties remained at the beginning of the ’00s regarding the steam explosions potentially resulting from interactions between a hot corium and the coolant. This conclusion explained the launch of the international SERENA programme described below, in line with the conclusions of OECD’s “Technical opinion paper on fuel coolant interaction” and with the summary
report published by OECD in 2001 concerning the nuclear safety research conducted in the OECD countries, which show the usefulness of continuing R&D on the corium–water interaction [52].

The OECD international SERENA programme took place between 2001 and 2005, to provide a state of the art on steam explosions resulting from the interaction between hot corium and the coolant in a core melt accident and evaluating the existing codes’ ability to describe this interaction. It showed that there were many differences of opinion between the experts, mainly due to the few experimental results available, highlighting the need for a new experimental programme.

This programme was implemented as part of a second phase of the programme, called SERENA-II, which took place between 2008 and 2012; its main objective was to study the effect of the corium’s composition upon the explosion in integral tests and obtaining results to improve the state of understanding of certain points and qualify the computer tools.

The studies conducted in the first phase of SERENA made it possible to confirm that there was little risk of the containment rupturing as the result of a steam explosion in the reactor vessel (“Alpha” mode) and that the studies conducted in the second phase of the programme should give priority to studying the steam explosions that might occur in the reactor pit after the reactor vessel fails. From the point of view of the phenomena involved, there are no fundamental differences between in-vessel and ex-vessel interactions (in the reactor pit). The difference lies in the conditions under which the fluids come into contact. In particular, the mode of corium transfer into the water differs: in the ex-vessel case, it depends on the conditions under which the reactor vessel is ruptured and generally occurs in the form of a wide, non-central jet that may possibly be ejected under pressure. The nature of the corium may also differ, notably with a high probability of separation of its metallic (oxidisable) and oxidised phases (in the corium in the lower head). Containment internal pressure is of course generally lower than in the reactor vessel, and the water is assumed to be colder. The studies conducted in this context have also led to the deduction that the main uncertainties regarding steam explosions were due to a lack of detailed results on the pre-mix region and on the behavioural differences between the corium and the simulants such as alumina (the material effect) when they interact with the coolant. A small number of the experiments showed that the interaction between the corium and the water generated less energy than that between the alumina and the water. This finding has to be confirmed and explained.

CEA (supported by IRSN and EDF) and KAERI, an institute in South Korea (supported by KINS, the Korea Institute of Nuclear Safety) proposed the second phase of the SERENA programme with the aim of obtaining further information on pre-mix flow configuration, as well as on the effects of the materials and geometry. Fourteen organisations participated in this phase: CEA, IRSN and EDF in France, the KAERI and KINS institutes in South Korea, IKE-Stuttgart (Institut für Kernenergetik und Energiesysteme) and GRS (Gesellschaft für Anlagen und Reaktorsicherheit) in Germany, JNES (Japan Nuclear Energy Safety) in Japan, AECL (Atomic Energy of Canada Limited)
in Canada, the US NRC (US Nuclear Regulatory Commission) and the University of Washington in the United States, JSI (Jozef Stefan Institute) in Slovenia, SKI (Swedish Nuclear Power Inspectorate) and KTH in Sweden, PSI (Paul Scherrer Institute) in Switzerland, VTT (Technical Research Centre) in Finland and SUEZ/TRACTEBEL in Belgium. This phase includes experiments in the CEA KROTOS facility (the facility was transferred from the JRC in Ispra to the CEA research centre in Cadarache and then improved) and the KAERI TROI facility [62]:

- the KROTOS facility consists of a small test cross-section (20 cm diameter and 1 m height of water), which uses 3–5 kg of corium or simulant. The facility was transferred from JRC ISPRA to Cadarache and improved. Notably, it is now equipped with a radioscopy system that is used to obtain more detailed information on the pre-mix and on the initial state of the explosion. The KROTOS facility is still mainly devoted to studying the explosion, however, as the corium’s low mass can, in principle, hardly be used to validate the models developed for the pre-mixing (some aspects of the pre-mixing, such as corium jet fragmentation, are sensitive to scale effects);

- the TROI facility has been improved in response to the programme’s needs and can inject up to 30 kg of corium or simulant into a tank larger than that of the KROTOS facility; in particular, it can be used to study explosion development in three-dimensional geometry.

The outcomes of SERENA-2 are not all favourable from a FCI risk assessment perspective but significant improvements in knowledge and modelling were obtained. A

![Figure 5.34. KROTOS (CEA, France) [37] and TROI (KAERI, South Korea) experimental facilities [62] – Main characteristics and instrumentation.](image-url)
negative outcome is the fact that the explosion strengths (peak pressures, impulses) were higher than in previous experiments (with the same melt composition). This is attributed to larger melt masses in the test sections at the moment of triggering the explosion. The analyses of the TROI results indicated also an important "venting effect", i.e. decrease of the pressure waves while travelling from the interaction zone to the walls. The pressure inside the interaction zone can be far higher that the resulting pressure at the wall. Due to this effect, in the hypothetical case of a central vessel break, the loads on the containment structures might be admissible or at least might not lead to immediate failure of the containment integrity (at least for the studied PWR geometry). Another positive outcome, from the point of view of the research efforts, was also the observation that the difference in explosion strengths owing to the exact composition of UO$_2$/ZrO$_2$ compositions was of second order.

5.2.3.3.3. Software

The MC3D computer code is developed and used in France to perform numerical simulations, notably of the pre-mixing and explosion phases [58, 59]. Its development by CEA to simulate steam explosions has mainly been financed by IRSN and partly by EDF. EDF ceased to support this code’s development in 2002 and then resumed its support in 2009 when it decided to participate in phase 2 of the SERENA programme. Since 2003, IRSN has been managing and developing the code in collaboration with CEA. Since 2006, the Slovenian JSI institute and the University of Stuttgart Institute of Research (IKE) in Germany have also helped to develop or qualify the code. The MC3D code is now considered as being one of the most advanced steam explosion simulation tools (mainly with JEMI/IDEMO [Germany, GRS/IKE], PM-ALPHA/ESPROSE [United States, UCSB] and JASMINE [Japan]) [59]. MC3D offers many functionalities described later in this document. It is distributed to various international bodies for studying the fuel–coolant interaction (as well as Direct Containment Heating (DCH)) in nuclear reactors.

A steam explosion computer code must process the many interactions between the different phases of the corium and coolant. This involves highly complex modelling with detailed numerical schemes, particularly in order to ensure its robustness. Furthermore, some codes such as MC3D are designed with the dual aims of obtaining results that can be used to assess safety in nuclear installations and improving our understanding of the phenomena involved. This dual purpose (studies and research) involves constraints that are often difficult to reconcile (robustness vs. accuracy).

In the MC3D code PREMIX application, the corium can be modelled in three different ways depending on whether it is in the form of a jet or in the form of droplets:

- the corium jet is modelled by a continuous field by means of a method of monitoring the volume (VOF-PLIC, see Figure 5.35); this numerical methodology is difficult to manage but its handling is a characteristic of the MC3D code, providing a wider scope of investigation than that of the other computer codes;

- the corium droplets are modelled by a field of drops by means of a Eulerian approach; the drops are created through fragmentation of the continuous field.
The MC3D code is also special in that it can take into consideration many non-condensing gases and corium oxidation by means of a parametric model. It should be remembered that the oxidation occurring during the explosion may result in a considerable increase in explosion energy. Unfortunately, the oxidation occurring under steam explosion conditions is poorly characterised (or even poorly understood) and the model is currently not sufficiently predictive.

There are fewer functional differences between the codes regarding the explosion phase modelling, and most of them use two fields for the fuel, namely a droplet field and a fragment field recording droplet fragmentation [59].

Some codes, such as PM-ALPHA and IDEMO, use what is known as the "micro-interaction" approach, in which the heating of a fraction of the water results in the pressure build-up. The MC3D and JASMINE codes’ models assume that, as in the premixing phase, the pressure build-up is due to film vaporisation around the fragments generated by the explosion. IRSN and IKE (using the IDEMO model) are jointly analysing the difference between the two approaches in order to better understand the implications of the various approximations and assumptions.

Although these tools’ predictive capabilities are still somewhat limited at this time (they include major uncertainties), they have significantly enhanced overall understanding of the phenomena and the multiple interactions. The MC3D code, despite the constant efforts made to improve the user interface, is still difficult to use because of its complexity, which is itself due to the complexity of the phenomena involved.
During the SERENA-2 programme, a remarkable evolution of the capabilities of the MC3D code but also of the JEMI/IDEMO codes was obtained. This concerned mainly the physical mechanisms of melt fragmentation and solidification. More recently, JASMINE (JNES) and TEXAS (UW) also received substantial improvements related to solidification and the melt drop description. One important outcome of the analyses conducted during SERENA-2 is the recognition that, in the reactor applications undertaken, mainly due to the large scale, a large fraction of drops are solidified and a large void develops around the melt jet. Both effects, together with the venting effect discussed before, lead to a strong reduction in the potential loads resulting from FCI on the reactor pit walls. It was also demonstrated that 3D calculations are practically feasible. This is important as it is believed that 2D approximations with a central jet are not fully representative. The real impact of asymmetry of both the flow and the reactor geometry is unclear but it can be investigated only with 3D models.

Following the SERENA-2 conclusions and the Fukushima nuclear accident, a five-year programme was launched in 2014. Called ICE, the programme involves the major actors involved in nuclear safety research in France, namely IRSN, CEA, EDF and AREVA. The University of Lorraine is also participating and the programme is partly funded by the French government. The project combines integral experiments in the KROTOS facility, measurements of corium melt properties, dedicated analytical experiments on fragmentation and oxidation and model development for the MC3D code. A significant step forward in knowledge and understanding is expected from the development and use of methods for directly modelling complicated phenomena such as fragmentation, film boiling or oxidation (“quasi” direct simulation). Such methods are expected to give insights that cannot be obtained from experiments due to the very specific conditions (high temperature, high pressures). Some of these developments are done directly in the MC3D code, through specialised new applications.

5.2.3.4. Summary and outlook

The results of the research on steam explosions may appear modest in light of the problems left to solve. This is due to the complexity of the phenomena involved in the interactions between the hot corium and the coolant, on the one hand, and to the difficulty of obtaining experimental data on these interactions for simulants whose composition is typical of a corium formed when a power reactor core melt accident occurs.

The complexity and costliness of the interaction tests using coriums containing uranium have led to the experiments being jointly conducted at the international level, notably resulting in the OECD SERENA programme. This programme aims to provide the missing experimental data for coriums representative of those found in a power reactor accident.

The computer codes include increasingly accurate modelling of the pre-mixing phase and the explosion phase. In this domain too, the work must be shared; this is done by means of partnerships or exchanges, notably in the context of the European SARNET network of excellence (Section 1.3.2). The most difficult key points to describe are jet fragmentation during the pre-mixing phase, corium solidification and its impact upon
the explosion. A better description of the pressure build-up process during the explosion is also required. These key points form the core of the French ICE project, started in 2014, for five years, which is expected to yield a further step in understanding, modelling and simulation capabilities.

From the power reactor safety point of view, it is generally agreed that there is little risk of a containment rupturing as a direct result of a steam explosion in the reactor vessel (at least in the case of reactors with a large containment, such as the French PWRs). As the flooding of the reactor pit is one of the measures taken or envisaged to limit the consequences of a core melt accident in the operational reactors (with the aim of cooling the corium in the reactor pit and slowing the interaction between the corium and pit concrete, as described in Section 5.3), however, the risk of the containment rupturing as a result of a steam explosion in the reactor pit must be evaluated. Questions also remain concerning the strength of the containment concrete structures, due to the pressure loads caused by a steam explosion.

It should be noted that, in the case of an EPR, the risk of a steam explosion in the reactor pit must be “practically eliminated” by setting up measures guaranteeing that the pit does not contain any water at the time of the corium melt.

Reference documents


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