In severe PWR accident studies, hydrogen risk refers to the possible loss of reactor containment integrity or engineered safeguard systems following combustion of the hydrogen released from a degrading core. Several phenomena contribute to hydrogen release in the course of an accident. As the core degrades, hydrogen is essentially produced by oxidation of zirconium in the fuel cladding and assembly structures and, to a lesser extent, by that of metals present in the RPV. If the accident is not controlled in-vessel, the molten core, or corium, can split into fragments on contact with water or be dispersed through the containment when the vessel fails; it then undergoes a second phase of oxidation. Interaction of the molten core material with basement concrete may lead to further hydrogen generation. Water radiolysis is yet another potential – albeit relatively insignificant, long term – source of hydrogen.

In the event of a primary circuit break, hydrogen is released to the containment atmosphere, where it mixes with air and steam. The location of this mixture on the Shapiro diagram (figure 1) determines whether some or all of it will be flammable. Several combustion modes are then possible, the most dangerous for reactor building integrity being the “premixed flame”, which develops in the flammable gas mixture and, unlike a diffusion flame, propagates from its ignition point to the various rooms and bunkers. If subjected to hydrodynamic instabilities and turbulence, the initially laminar deflagration (velocity = about 1 meter per second) may accelerate under certain conditions. Fast combustion regimes – fast deflagration (several hundred m/s), deflagration to detonation transition (DDT) and detonation (more than 1000 m/s) – are then achieved. It is these explosive phenomena, often resulting in locally significant dynamic loadings that constitute the greatest threat to containment wall mechanical strength.

The hydrogen risk was first identified some years ago and was already an issue in the WASH 1400 report (Rasmussen, 1975). Its existence was substantiated by the Three Mile Island (TMI-2) accident in 1979, when, ten hours after accident onset, a pressure spike of some 0.2 MPa was observed in the reactor containment. This phenomenon – attributed to a deflagration caused by hydrogen combustion originating from an electrical spark – did not, however, have notable consequences. Since TMI, the nuclear safety authorities, those of France in particular, have made sure that hydrogen risk is accounted for in all existing reactors and those still on the drawing board.
Assessing the consequences of such risk requires the capability both to understand associated physico-chemical phenomena and to gage the effectiveness of available countermeasures. IRSN has thus set up an R&D program intended to enhance such capability, in line with the needs of its expert assessment role.

The following pages provide a description of this program. A recap of R&D requirements relating to hydrogen risk mitigation/elimination strategies for existing or future reactors and of answers provided by or expected from this program are discussed under several headings: hydrogen production during severe accidents, distribution of the gas through containment rooms, possible combustion modes and mitigating measures. The overview does not include studies of containment response to explosion-induced mechanical loadings.

**R&D required to enhance hydrogen risk assessment**

In the existing reactor population, a pragmatic approach has thus far been taken to hydrogen risk evaluation. This has primarily consisted in estimating impact on the containment of the (near static) load resulting from a (slow) deflagration. While such a phenomenon is seen as an inevitable consequence of a severe accident, fast deflagration or detonation is not certain to occur in a PWR containment. It has in fact been established that, for a quantity of in-containment hydrogen equal to that potentially generated by oxidation of the cladding portion around the fuel, the pressure spike produced by combustion would be close to the estimated containment leakage pressure value. In such a situation, adequate leaktightness could not be guaranteed, whether for a 1450, 1300 or 900 MWe unit. The French safety authority has therefore required EDF to install catalytic hydrogen recombiners in all its plants by the end of 2007. The number and location of these recombiners must be such as to eliminate risk of containment integrity loss due to deflagration and to also mitigate risks related to local hydrogen concentrations (flame acceleration). EDF is likewise responsible for demonstrating this, by means of representative accident scenario calculations.

The general strategy for not-yet-built reactors, and specifically the EPR project, is to eliminate, by suitable design, the global detonations that could otherwise threaten containment integrity, while taking appropriate measures to prevent dynamic phenomena such as fast deflagration or DDT. This means eliminating locally high concentrations of hydrogen, wherever possible through suitable design of reactor internals and by use of mitigation technologies such as catalytic recombiners. Where it cannot be demonstrated that local hydrogen concentration in the containment remains below 10%, special criteria can be set for prevention of flame acceleration (FA) and DTT (see section V), provided they are fully justified and validated. The containment must also be dimensioned to withstand deflagration of the maximum quantity of hydrogen containable in the reactor building, after allowance for the adopted preventive measures.

In selecting pertinent scenarios for in-containment hydrogen release/distribution kinetics, designers must apply a systematic, deterministic approach that also credits uncertainties and accounts for risk mitigation devices.

As technical support agency for the French safety authority, IRSN assists the former in assessing the validity of already mentioned operator demonstrations, both for reactors now in service and those to come. Given the current state-of-the-art, the Institute considers that further clarification of certain issues is necessary to back up such demonstrations. These issues, which are recalled below, are the subject of an R&D program intended to bolster the Institute’s own judgments on future evaluations made by the plant operator.
Hydrogen production and particularly the kinetics of this process, are among the main factors affecting risk and, consequently, the design of mitigation devices. These factors are usually well estimated for the first phase of the accident scenario, but there are still many uncertainties about advanced core degradation (melt down and relocation of materials, corium debris formation, core slump to the lower head), and the consequences of core reflood. The true impact on risk of hydrogen appearing at the corium/concrete interaction stage also needs further clarification, since this hydrogen, if it is not burned as fast as it appears, could cumulate with that produced (and not previously burned) in the vessel. Accurate prediction of hydrogen distribution in the containment is also essential to IRSN rulings on risk of dynamic phenomena occurrences. In this respect, pointwise codes seem inadequate for highly stratified gases, and multidimensional codes, whose computational times are still prohibitive, lack validation. In addition, the criteria used to characterize risk of fast deflagration and DDT remain to be validated for all the conditions likely to occur in the reactor (high degrees of stratification, complex geometries, etc.). Because at some local points, these criteria may also be temporarily exceeded during an accident, there is need for developing combustion codes and validating them over the whole range of possible flame velocities.

**Hydrogen production**

As already stated in the previous paragraph, in-vessel hydrogen production is a well known phenomenon, successfully modeled for phase one of degradation, in which core geometry remains nearly intact. In particular, physical models for IRSN-developed core degradation codes VULCAIN (simplified modeling) and ICARE (detailed modeling) have been validated on the basis of Phoebus FP test results.

Actions included in the R&D program thus focus on reducing uncertainties associated with hydrogen production and production kinetics in subsequent core degradation phases (advanced degradation, degraded core reflooding, vessel failure and post-failure corium/concrete interaction). For advanced degradation, codes are compared with sensitivity studies to assess uncertainties and prioritize parameters impacting the production process. Figure 2 shows various results obtained (along with discrepancies) for a two-inch primary pipe break scenario. IRSN is devoting significant efforts (not discussed here) to improving physical models for this phase, thereby eliminating such discrepancies. Systematic hydrogen production studies have likewise been conducted as part of level two probabilistic safety assessment. Such studies have identified the most penalizing factors for hydrogen production and have quantified their effects: initially low residual heat, low primary pressure, water input to the degraded core and condensation resulting from cooldown via the steam generators.

A summary of current knowledge on degraded core reflooding has been compiled and could give rise to a new experimental program. Calculation of hydrogen production in the vessel failure phase due to direct containment heating shows that the hydrogen quantity produced is linked to initial level of corium oxidation and to that of corium dispersal, which itself depends on several parameters, mainly primary pressure, water input to the degraded core and condensation resulting from cooldown via the steam generators.

Corium/concrete interaction involves two phases. A first, “short-term” phase, immediately after the corium pours onto the basemat, is characterized by very fast concrete erosion, associated with intensive releases of hydrogen – essentially due to oxidation of molten core zirconium and chromium content – and of carbon monoxide. This phase is correctly predicted by...
existing computer codes. During the second, "long-term" phase, whose kinetics are much slower, release of the same combustible gases results mostly from oxidation of iron in the corium. There is much uncertainty surrounding this phase; but because it generates large quantities of inerting gas, it is also less significant in terms of combustion risk.

**Hydrogen distribution in the containment**

During a severe accident initiated by a primary pipe break, steam flowing through the break condenses on cold walls and forms convection loops in the containment volume. These loops transport the hydrogen produced in the accident and distribute it through the containment. Depending on how mixing occurs in the containment atmosphere, this distribution will be either homogeneous or heterogeneous. In the latter case, local concentrations of hydrogen may be higher than the flammability limit of the gas mixture. Moreover, hydrogen distribution can be modified by use of spray systems that homogenize it and cause steam to condense on spray droplets, with the concomitant risk of deinerting the mixture.

Later on in the accident, after vessel failure, in the fast phase of hydrogen release by corium/concrete interaction, high hydrogen concentrations may occur near points where hot gases escape from the reactor pit. To predict hydrogen distribution in the containment, IRSN uses codes based on a multicomartment or multidimensional approach. The first of these code “families”, of which the TONUS 0D module is a notable example, solve mass and energy balance equations for control volumes (compartments). The conservation of momentum equation is solved in simplified form by way of pressure losses between the compartments. Such codes have demonstrated their ability to compute hydrogen distributions in large- and small-scale experiments with or without containment spray. In contrast, they cannot predict all possible flows, particularly if concentration gradients occur (due to stratification, jets, etc.). Multidimensional codes such as the 3D module of TONUS overcome this handicap by locally solving conservation (of mass, momentum, energy) equations and transport equations for the different species. These equations are coupled with turbulence and heat and mass transfer models to account for condensation.

Use of these codes is limited by the complex geometry of the containment and the sometimes excessive costs and times involved in such calculations.

The purpose of the TONUS code, which has been under development since 1995, is to provide a hybrid multicompartment and multidimensional approach that enables incorporating, in a single tool, all phenomena relative to hydrogen risk in a PWR containment. By coupling TONUS 0D and 3D modules, it is possible to process zones of probable homogeneous concentration with a multicompartment approach and to reserve multidimensional processing for zones where concentration gradients are likely.

To qualify multidimensional codes, the local values of all variables, including temperature, gaseous species concentrations, average rates for different flow regimes, and their fluctuations must be experimentally determined. The corresponding experiments thus require a complete set of detailed measurement devices.

This constraint is accounted for in the TOSQAN test facility, whose main purpose is to qualify the models included in TONUS, whether for condensation on containment walls or for heat and mass transfers at the sump/atmosphere inter-
The goal of experimentation in TOSQAN is to determine changes in global variables (condensation rates, pressures) and to characterize flow regimes by measuring temperature fields, velocities and specie concentrations. This is done by steam injection at a flow of 0.3 g/s to 30 g/s, lined up with the enclosure axis.

To meet the specified objectives, TOSQAN is instrumented to afford detailed, mainly local measurements. These measurements are divided into two categories: “intrusive” measurements of temperatures in gas and on walls, and of specie concentrations (using mass spectrometry), and optical measurements of velocities and specie concentrations (using Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) and Raman spectrometry respectively).

For TONUS code qualification, a test grid was defined to cover a set of specific thermodynamic conditions for studying condensation on the side wall of the test facility; this allows calculation of turbulent flow regimes (with natural, forced or mixed convection) illustrative of those encountered in severe accidents. This grid is now being applied. Figure 4 shows radial velocity profiles measured by LDV for permanent condensation conditions corresponding to injection of 10 g/s of steam.

On completion of these experiments, calculated-to-experimental data (C/E) comparisons will be used to determine which wall condensation models are best suited to TONUS and how well calculated results correlate with measured flows, temperatures and concentrations. Following these comparisons, further TOSQAN tests of helium-steam-air mixtures will assess the impact of spraying and of sump-to-atmosphere heat transfers on specie distribution. Allowance will be made for results of larger-scale confirmation tests performed on more complex, multicompartment geometries, whether already scheduled or being considered by CEA’s nuclear energy division (DEN) for the MISTRA facility.
Hydrogen combustion

As stated in the introduction to this article, when the hydrogen-steam-air mixture becomes “flammable” in Shapiro diagram terms (figure 1, page 28), several combustion modes — laminar deflagration, fast deflagration, deflagration to detonation transition (DDT) or detonation — are possible. Which of them occurs is largely dependent on the peak hydrogen concentration reached in the containment and the distribution of this gas through the rooms.

Better understanding of the mechanisms involved in this process has led to a set of criteria for homogeneous mixtures that reflects the conditions required for each combustion mode. The first of these, the \( \sigma \) criterion, relates to flame acceleration (FA). \( \sigma \) is the expansion factor of a mixture, that is, the ratio of its fresh gas to burned gas densities at constant pressure, and is also an intrinsic property of the mixture. Specialists consider that a mixture whose \( \sigma \) value is less than a critical \( \sigma \) limit cannot trigger significant FA (beyond 400 m/s).

The critical \( \sigma \), which depends on initial gas temperature and flame stability, was determined by results of multiple experiments on different scales, in different geometries. Note that a flame propagating in a mixture whose \( \sigma \) exceeds this value is liable to accelerate, but only in a favorable geometrical configuration. Conditions for DDT have been similarly determined and are based on comparison of the characteristic length scale of the geometry to detonation cell size, denoted \( \lambda \). The cellular pattern produced by interaction of the various waves attests the multidimensional structure of the detonation: the cell size \( \lambda \) shown in figure 5 characterizes the sensitivity of the mixture.

The resulting criteria are formulated as follows:
- in a tube of diameter less than \( \lambda \), no DDT can be initiated;
- in a room or set of rooms whose maximum, unobstructed length is less than \( 7\lambda \), no DDT can be initiated.

The criteria mentioned above justify an a priori exclusion, without calculation, of FA and DDT risks for a number of mixtures, but not for all of the possible accident sequences. Specific models are therefore required to evaluate the resulting mechanical loadings on the containment walls.

In the TONUS code, combustion is processed differently, depending on how space is discretized in each case:
- in the lumped parameter module, the flame develops spherically in each compartment before propagating to adjoining compartments via atmospheric junctions. The Peters correlation accounts for the impact of turbulence level on the spatial velocity of the flame: this model, associated with a low-Mach algorithm, is especially well suited to describing low velocity deflagrations;
- the “3D finite element” module incorporates conventional approaches; the Favre-averaged Navier Stokes equations are solved in a semi-implicit scheme. The chemical source term is...
the “eddy breakup” or “Arrhenius” type. These modes apply to the complete range of turbulent deflagrations, and turbulence is evaluated using a $k-\varepsilon$ model;

- in the “3D finite volume” module, compressible “Van Leer-Hanel” and “Shock-Shock” solvers for reactive Euler equations enable processing of fast flames (CREBCOM model) and detonations.

While slow flames and detonations can be fairly well calculated with existing models, more progress is needed in the area of fast turbulent deflagrations. Recent experiments have therefore centered on the study of this regime. Validation of criteria is continuing as is study of their application to heterogeneous mixtures, through the two experimental programs mentioned below.

The objective of Europe’s HYCOM program and the RUT tests underway at the Kurchatov Institute (Russia), under the coordination of IRSN, the FzK (research center in Karlsruhe, Germany) and the European Union (EU) is to build up a large database from results of hydrogen-air mixture combustion tests conducted on both small scale (tubes) and large scale (RUT facility schematized in figure 6) for subsequent computer code qualification.

As an example, figure 7 shows a calculation-to-experiment comparison for an RUT flame acceleration test. Flame front propagation is monitored during this test using photodiodes between the 65 m (ignition) and 35 m points in the duct. Calculations are performed by the combustion module of the multicompartment TONUS code.

Through another partnership, with CNRS in Orleans (France), flame propagation is being studied in a vertical tube obstructed by a simulated steam generator and opening into a dome. This configuration has been identified as the most likely to accelerate a flame in a PWR-type containment.

**Hydrogen risk mitigation technologies**

Mitigation devices are intended, in an accident sequence, either to act on at least one of the two reactive components of the hydrogen-steam-air mixture or to increase the “inerting” content of the containment atmosphere. The point representing the mixture on the Shapiro diagram (figure 1, page 28) must therefore be situated outside both the detonation zone and, where necessary, part of the ignition zone.
As stated in earlier paragraphs on R&D for hydrogen risk assessment, the French safety authority has selected catalytic recombiners as the mitigation technology for all French NPPs. The role of recombiners during an accident is to reduce hydrogen concentration in the containment. These devices (some forty per plant unit) offer a number of advantages: they have modest operating constraints, are fully autonomous and promote thorough mixing of containment gases when in service.

A recombiner typically comprises a “conventional” catalyst material (platinum and palladium on an alumina support) contained in a metal frame whose function is to optimize gas circulation through the catalyst (bed of pellets or row of vertical plates). This is achieved by natural convection of the gases heated by the exothermic reaction \( 2H_2 + O_2 \rightarrow 2H_2O \) that takes place on contact with the catalyst. The reaction is self-sustaining (thus the commonly used term “PAR” or “passive autocatalytic recombiner”), but is nevertheless limited by diffusion of reactants (\( H_2 \) and \( O_2 \)) and their products (\( H_2O \)) in the recombiner. The recombination rate \( \frac{dm_{H_2}}{dt} = K_{H_2} \) is of the order of 0.3 grams of hydrogen per second for a medium-sized recombiner in an atmosphere containing 4% hydrogen (with oxygen in excess).

In 1996, with financial backing from EDF, IRSN launched an experimental program for study of hydrogen recombiner performance in a representative accident atmosphere, with emphasis on catalyst poisoning by fission products released from the damaged reactor core. This program, which is now completed, was conducted in the H2PAR facility (figure 8) at Cadarache, a 1/22th scale (1/10,000th by volume) containment mockup designed to reproduce, with non radioactive components, most of the physico-chemical parameters of an accident atmosphere. The original design of this facility (use of a flexible, 7 m³ Mylar “tent” with metal frame) affords fully safe handling of potentially explosive hydrogen-air mixtures, at temperatures of up to 90 °C.

Three types of industrial recombiners, from three different manufacturers (SIEMENS, NIS, AECL) were tested in H2PAR. The experimental sequences – of which more than thirty were completed from 1996 to 2000 – included reference tests (in different \( H_2O \)-air-H\( _2 \) mixtures) and other tests in the same mixtures to which were added potential poisons. These poisons were produced in an induction furnace, by vaporizing a chemical charge illustrative of materials released under accident conditions by a PWR core.

In none of these representative tests was there evidence of performance losses due to poisoning. Only where specific poisons (such as AgI) were used at much higher concentrations than expected during core meltdown, could a link be established between lower recombiner performance and catalyst poisoning (figure 9). These conclusions were reinforced by analytical experiments performed in conjunction with the Institute for research on catalysis (at the CNRS Villeurbanne campus).

Some fifteen additional tests then investigated the conditions under which the \( H_2O \)-air-\( H_2 \) could ignite on contact with a recombiner in operation. Results show (figure 10) that combustion can indeed be initiated in the recombiner and propagate downward when hydrogen content exceeds 6% (in a dry atmosphere). This draw-
back was accepted by the safety authority “due to the low level of energy required for ignition and the multitude of other possible causes of deflagration in a PWR containment.” It should, however, be confirmed that if a flame propagates from one of the recombiner locations planned by the operator, any loadings induced in structures or equipment remain acceptable.

Conclusion

IRSN research and development efforts regarding hydrogen risk have already yielded results. These studies have provided support for the decision to install catalytic hydrogen recombiners in all the units of French nuclear power plants. A prerequisite for using recombiners is a good understanding of how they “behave” under conditions illustrative of severe accidents.

Tests performed in the H2PAR facility have shown in particular that recombiner performance is not significantly affected by the aerosols released during a core melt accident. These tests also served to determine the limits, in terms of mole fraction of hydrogen, beyond which a hydrogen-steam-air mixture in the vicinity of the recombiner could ignite.

However, studies of representative accident sequences indicate that, even with recombiners installed, it is difficult to preclude formation of a combustible mixture at every point in the containment and at all times. Criteria which, if strictly observed, can eliminate risk of FA and DDT, were therefore devised after wide-ranging international research in which the RUT facility and the experimental program conducted by the Kurchatov Institute played an essential role.

In the years to come, R&D will concentrate on obtaining better estimates of hydrogen sources.

Tests performed in the H2PAR facility have shown in particular that recombiner performance is not significantly affected by aerosols released during a core melt accident.
local concentrations of the different gaseous components and risk of burn propagation.
The greatest uncertainties in hydrogen source estimates concern core slump to the vessel bottom head and hydrogen production kinetics in a hypothetical degraded core reflooding scenario. An R&D program is being planned at the Institute to improve knowledge of these situations. For local hydrogen concentrations, current TOSQAN and MISTRA programs are directed toward validating TONUS code distribution processing. The results of these studies, in combination with multicompartment approaches, will in future afford more precise assessment of the potentially most concentration-critical zones of a reactor. As regards the third issue mentioned above, IRSN has initiated additional R&D actions in two areas: evaluation of safety margins for flame acceleration criteria under conditions illustrative of the reactor environment (geometries including heterogeneous compartments and concentrations), and development and validation of combustion models for such conditions. These actions are the focus of a European program (HYCOM), using the modified RUT facility, of joint experimental studies (IRSN and CNRS-Orleans) and of development, within the TONUS code, of combustion models, either in simplified versions for use in multicompartment geometries, or in multidimensional form.

In conclusion, the R&D actions described above will provide refined analysis capability for the present day reactors along with qualified tools for assessment of foreseen measures for future NPPs.