USE OF 3D CFD SIMULATIONS TO ASSESS AND MITIGATE CONSEQUENCES OF AGGRESSIONS IN NUCLEAR BUILDINGS

During the past decades, computational power has become affordable and 3D computation capabilities have strongly risen in nuclear industry, just like in the other industries.
The insights of physical phenomena provided by CFD enable to enhance and adapt the design of future NPPs or others nuclear utilities as well as supporting safety justification of currently running facilities in a context where regulations evolve to take into account the experience feedback from severe accidents.
In this frame, FRAMATOME has used these 3D CFD methods in a collection of real site situations such as:
– Justification of the venting and heat removal capability of Pu dry storages
– Justification of Dry Fuel Assemblies storage safety during the fire of a handling truck.
– Justification of the acceptability of the ambiance inside a fuel building in the case of the total loss of cooling capabilities.
– Assessment of humidity field inside a fuel building during loss of heat removal capabilities.
In all these cases, CFD enabled a better understanding of the real physical problems at stake and either to prevent system upgrade by justifying and quantifying hidden margins or to design adapted solutions for the problem.
When dealing with such complex physics for safety justification, two main points (mastered by FRAMATOME) are essential for a good quality analysis:
– Validation of CFD code must be appropriately demonstrated
– Computational time must be mastered and kept to a minimum so as to enable sensitivity analysis and to be compatible with the timing of projects.

1. INTRODUCTION

During the past decades, the cost of computational power has greatly decreased, the CPUs being more and more powerful and affordable. The consequence of this for the nuclear industry is that detailed 3D analyses at the scale of a facility or of a building are now within the reach of industrial applications.

This paper will describe the benefits from using CFD for the utility through examples. These benefits are mainly:
- A better understanding of the physical phenomena at stakes during the aggressions, enabling to design solutions that address the actual issues at stake.
- The demonstration of margins regarding safety criteria by taking into account the 3D nature of physics.

2. FIRE PROTECTION

2.1. The choice to go 3D

Regarding fire protection of nuclear buildings, the issue is to demonstrate that no sensitive equipment is put at risk in the event of a fire. A second issue is to demonstrate that the fire does not propagate.

A large panel of possibilities is offered to safety analysts:
- Use of handbooks and tabulated results
- Use of 0D or 1D codes such as CDI, CFAST, MAGIC
- Use of 3D codes such as FDS or standard CFD codes

While the use of the first two possibilities is widespread and generally well known for the safety authorities, they can be quite conservative and as a consequence lead to the conclusion that a large amount of work can be necessary to mitigate the consequences of the fire. These works can include sectorisation work, civil reinforcement work and protection work through the use of fireproof paint. All of these works can lead to high costs due to:
- Building unavailability during the upgrade works
- Cost of the work themselves.

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FRAMATOME

USO DE SIMULACIONES CFD 3D PARA EVALUAR Y MITIGAR CONSECUENCIAS DE AGRESIONES EN EDIFICIOS NUCLEARES

Durante las ultimas décadas, el poder computacional se ha hecho más asequible y las capacidades computacionales 3D han crecido sustancialmente en la industria nuclear, así como en otras industrias.

La visión de los fenómenos físicos que proporcionan los códigos CFD permite mejorar y adaptar el diseño de futuras centrales nucleares u otras instalaciones nucleares así como dar soporte para justificaciones de seguridad de centrales en operación, en un contexto donde la regulación evoluciona para incorporar las lecciones aprendidas de los accidentes severos.

En este marco, Framatome utiliza estos métodos CFD 3D en un ábanico de situaciones reales como por ejemplo:
- Justificación de las capacidades de venteo y eliminación de calor de almacenamientos en seco de Pu.
- Justificación de seguridad del almacen de elementos combustible en seco durante el incendio de un camión de transporte
- Justificación de la habitabilidad dentro del edificio de combustible en caso de pérdida total de capacidad de refrigeración
- Análisis de humedad dentro del edificio de combustible en caso de pérdida total de capacidades de refrigeración

En todos estos casos, la simulación CFD permite una mejor comprensión de los problemas físicos reales, lo que permite a su vez o bien evitar la modificación de sistemas mediante la justificación y cuantificación de márgenes escondidos, o bien diseñar soluciones más adaptadas al problema.

Cuando se trata de lidiar con justificaciones de seguridad sobre una física tan compleja, dos puntos (que Framatome domina) son clave para un análisis de calidad:
- La validación del código CFD ha de ser demostrada de manera robusta.
- Tiempo computacional debe ser optimizado al mínimo que permita un análisis de sensibilidad, a la vez que sea compatible con los plazos de los proyectos.

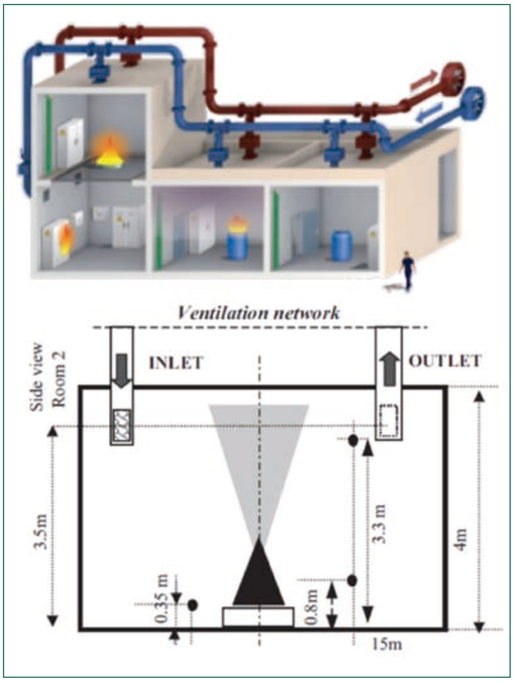

Figure 1. Presentation of the DIVA facility.

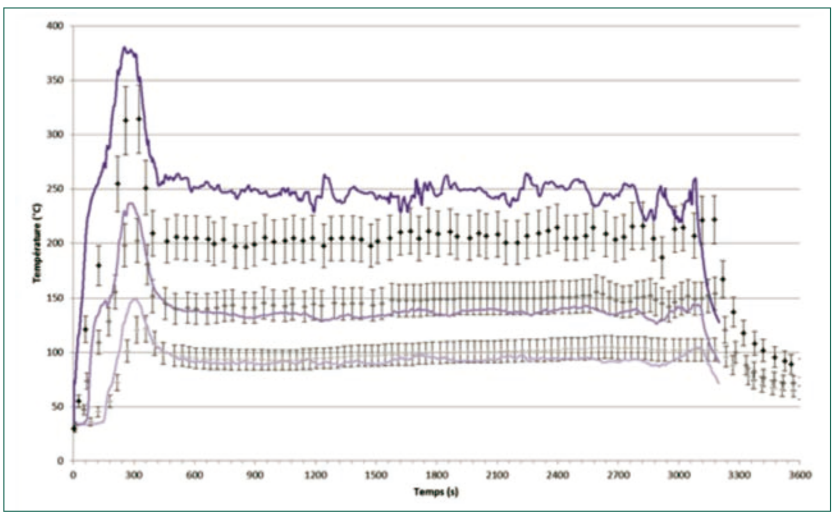

Figure 2. Gas temperature.

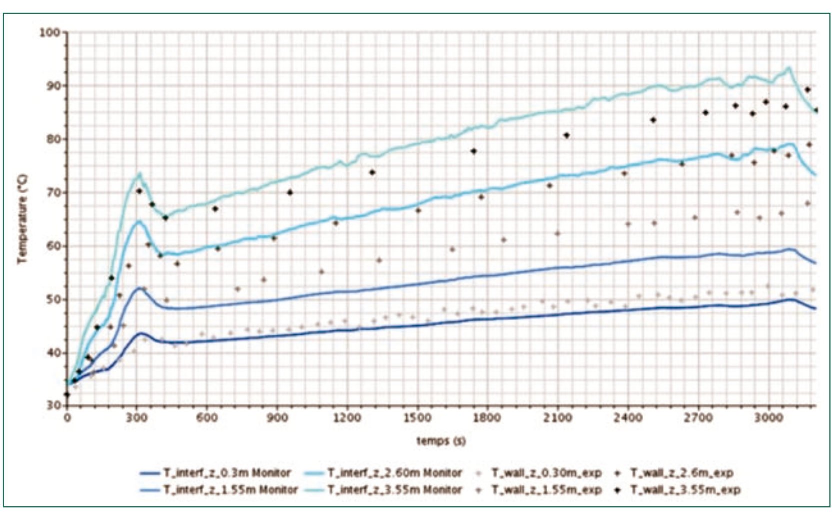

Figure 3. Wall temperature.

For this reason, it can be interesting to study the physics of fire with more details, and to take into account the 3D nature of the flow inside the room. This is especially true for those buildings or rooms where the fire potential is high and where « standard » approaches conclude to high risk. Due to their higher complexity, 3D approaches are usually used after an initial screening of the facility to detect the most sensitive locations. Other rooms can be handled with « standard » methods.

Once again, several solutions are available on the market to do so. A popular solution is the use of the open source code FDS, offering a license-free solution to study the consequences of fire. After benchmarking with its own nuclear validated CFD solution based on commercial code STAR-CCM+, FRAMATOME has made the choice to use STAR-CCM+ for the study of fire consequences in 3D for the following reasons :

- Synergy with other nuclear applications and with the FRAMATOME validation file for STAR-CCM+
- Higher operability and flexibility. Better capacity to handle large, complex volumes through an efficient link with CAD
- Better scalability (lower computational time) on FRAMATOME computer
- 3D heat conduction models readily available

In order to be able to use CFD computations for safety analysis, it is first required to demonstrate the validation of the codes for this purpose.

2.2. Validation of CFD codes

The demonstration of validation of CFD codes is performed in four steps:

1. A PIRT analysis is made to select the physical phenomena of interest
2. The validity of the code is demonstrated on separate effect tests that are focused on a single particular physical phenomenon involved in
3. The validity of the code is demonstrated on integral tests that combine all physical phenomena at stake, ideally at scale 1 or with a representativity of the industrial phenomena
4. If required, uncertainties are assessed.

For STAR-CCM+, the validation available at FRAMATOME covers the point 1 and 2. A specific R&D program has been launched to cover the points 3 and 4. This program relies on several tests from different organization. One good example is the PRISME D1 test performed by IRSN in its facility DIVA (reference [1]). Figure 1 presents the test facility where http fuel ($C_{12}H_{26}$) has been burnt.

A benchmark of STAR-CCM+ predictions of the consequences of the fire with the test results has been undergone and is presented on Figures 2 (for the gas temperatures), 3 (for the wall temperature) and 4 (for the concentration of gases in the room). The comparison shows an excellent correlation between computational results and test results, demonstrating the capacity of the CFD code to predict the behavior of the containment under fire.

In addition, a quantification of uncertainties has been made based on

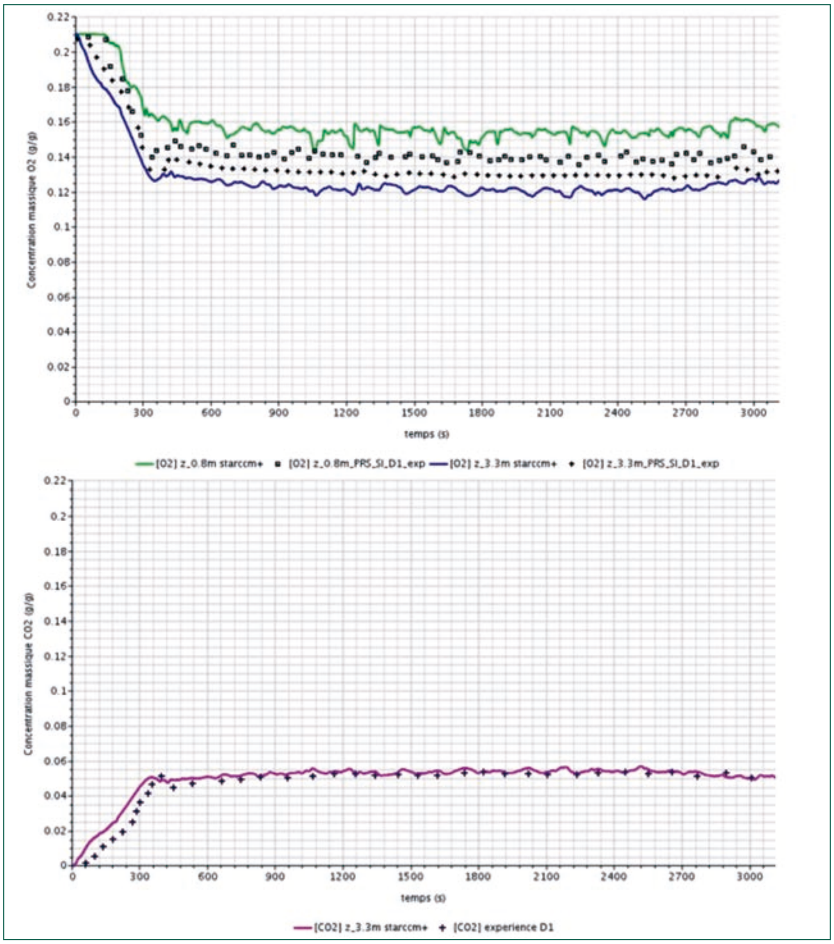

Figure 4. O_2 and CO_2 concentration in the room.

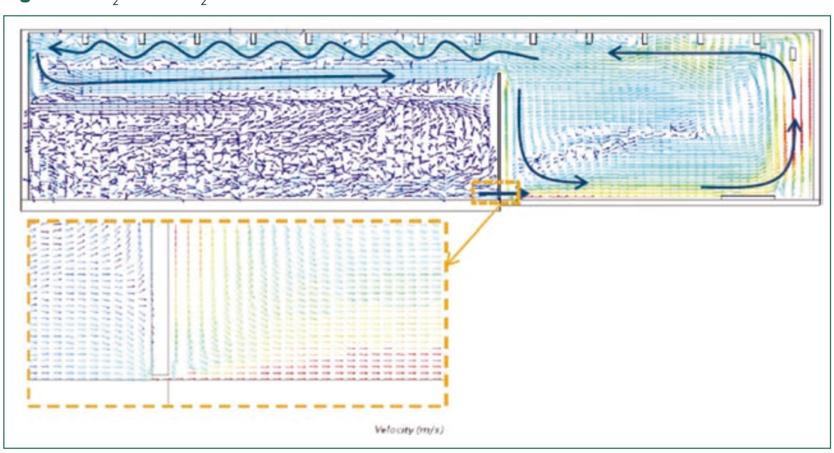

Figure 5. General hydraulics inside the storage during the fire.

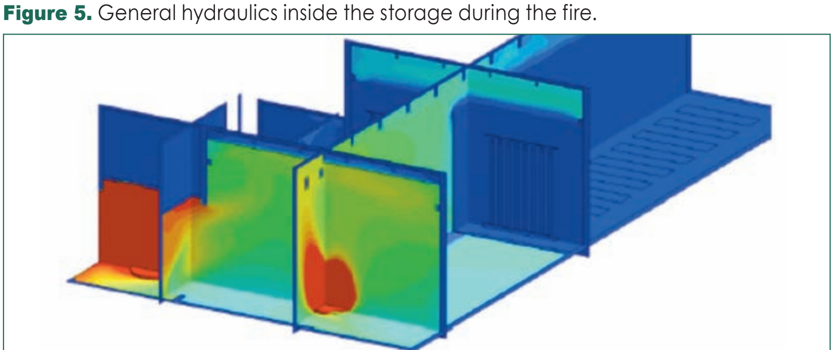

Figure 6. Temperature field inside the building during the fire.

a large sensitivity analysis on unknown physical properties (such as emissivity of the soot, exact conductivity of the concrete…) showing the stability of the CFD result and the confidence that can be given to it.

Based on this validation, industrial cases have been investigated.

2.3. Industrial application

Among the various industrial applications where this method has been used, one can quote the study of a fuel assembly dry storage building. The industrial issue is the following: in this building, truck come and go to load or remove fresh fuel assemblies, the building being used as a buffer storage between the fuel processing facility and the plant. At any given time, there might be up to more than 100 fuel assemblies stored, waiting to be sent to a nuclear plant.

The utility has then to demonstrate that, in the event of the fire of a truck

- The containment would resist
- The fuel assembly integrity would not be questioned.

Initially, the safety demonstration was based on the use of fire protection systems. Making these systems able to survive during the whole fire would potentially have induced tough discussions with safety authorities and protection works.

Studying this situation FRAMATOME safety team decided to investigate the consequences of the fire in 3D, without the consideration of fire protection equipment.

The 3D study of the building enabled to demonstrate that the high temperature zone was limited to the loading zone. See for instance Figure 5, showing the stratification of hot gases inside the storage and Figure 6, plotting the temperature field on several section planes after a few minutes of fire.

As a consequence, it has been possible to demonstrate that fuel assemblies were not damaged by the fire, even without the consideration of some fire protection systems. The upgrade work could be limited to a minimum and the operating procedures could remain not modified, hence huge savings and easier operation.

This is a typical example of how 3D simulation, embedded inside a more global safety analysis, can bring value by at the same time enhancing safety demonstration and limiting modification costs.

3. VENTING STUDIES

The venting of nuclear buildings is a complex matter that must comply with a lot of constraints (containment, filtration...). Usually the tools used rely on network analysis based on pressure drop and blower characteristics in a 1D manner.

These tools are well suited for network analysis, but when accidental conditions arise in heat loaded rooms, natural convection will take place and standard network codes will not be able to represent it accurately anymore.

FRAMATOME faced this type of problems in the justification of Plutonium dry storage facilities to justify the safety of the building in case of a total loss of heat sink in a post Fukushima context, or in the frame of thermal analyses in the case of loss of heat sink inside a PWR reactor building.

3.1. The choice to go 3D

When heat sink or even the full venting system is lost, natural convection takes place in the large rooms comprising the nuclear buildings. This convection is driven by the temperature difference between the air heated by the hot equipment (it might be active matter such as Plutonium or a safety equipment such as the motor of a safety pump) and the air of the rest of the building remaining cold for a long time. This situation can last very long as the thermal inertia of the heavy containment is large and will continue to cool down the heated air for days.

Such situations are heavily 3D and 1D network code cannot handle them correctly. Once again, in many situations, the margin is such that a hand computation or a simple analysis is sufficient to demonstrate the existence of margins. Nevertheless, for those complex and extremely penalized situations that utility have to face in a post Fukushima context, the use of 3D analysis can provide much needed margins.

3.2. Code validation

The same approach as the one described in paragraph 2.2 has been used and will not be reproduced in this article.

For separate test, the validation of the code STAR-CCM+ relies on experiments from the literature on natural convection in laminar and turbulent conditions.

Integral tests include dedicated experiments and real on site predictions such as the conditions in the atmosphere of French Superphenix plant during decommissioning and actual temperature measurements performed on site in a Plutonium dry storage in France.

Finally, available measurements enabled to successfully benchmark

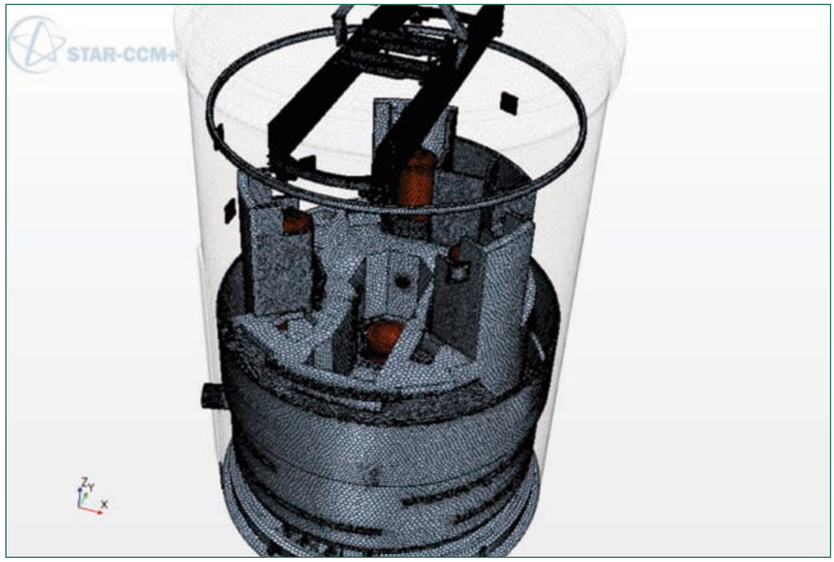

Figure 7. Reactor Building mesh overview.

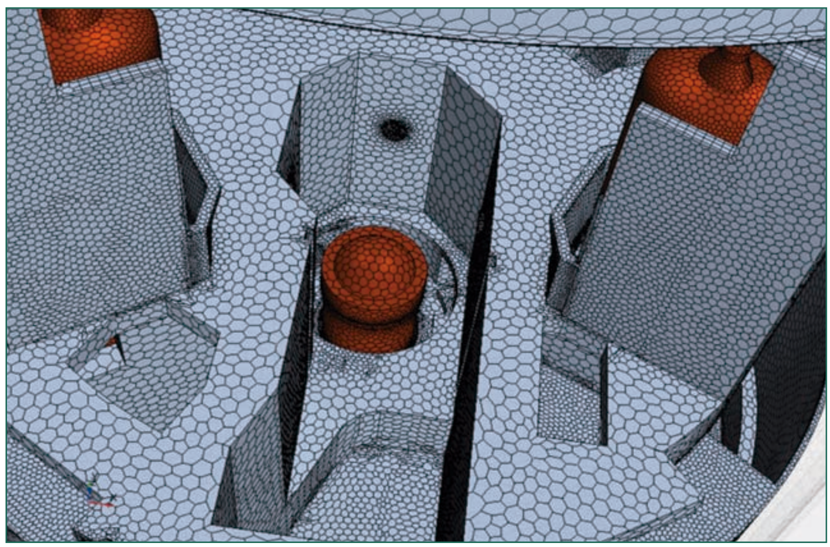

Figure 8. Zoom on the RPV and SG.

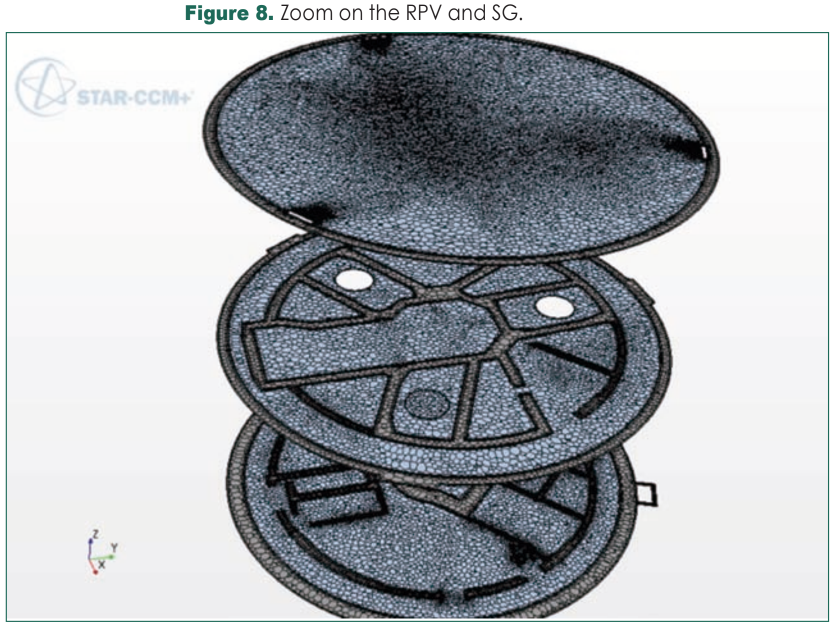

Figure 9. Mesh density at different levels.

CFD thermal computations with measurements inside a French PWR reactor building.

3.3. Industrial applications

The industrial applications covered by CFD for the thermics of large building is large but often covers proprietary data. For the purpose of this article the example used is an R&D worked performed in Framatome in 2016 regarding the thermics of a French 900 MWe reactor building.

The example concerns a normal shutdown of the reactor. In that case, the ambient temperature of the reactor building will slowly decrease. It can be of industrial relevance to determine at which rate this temperature will decrease and how to speed it up, as operational constraints require that the ambient temperature inside the building has decreased before starting heavy operations inside the building.

The challenge for such computation is the complexity and the size of the building: see Figures 7, 8 and 9. The cell count of such models is above 10 million which is a minimum for a good accuracy. This implies that computation time can be quite long. This point will be discussed in paragraph 4.

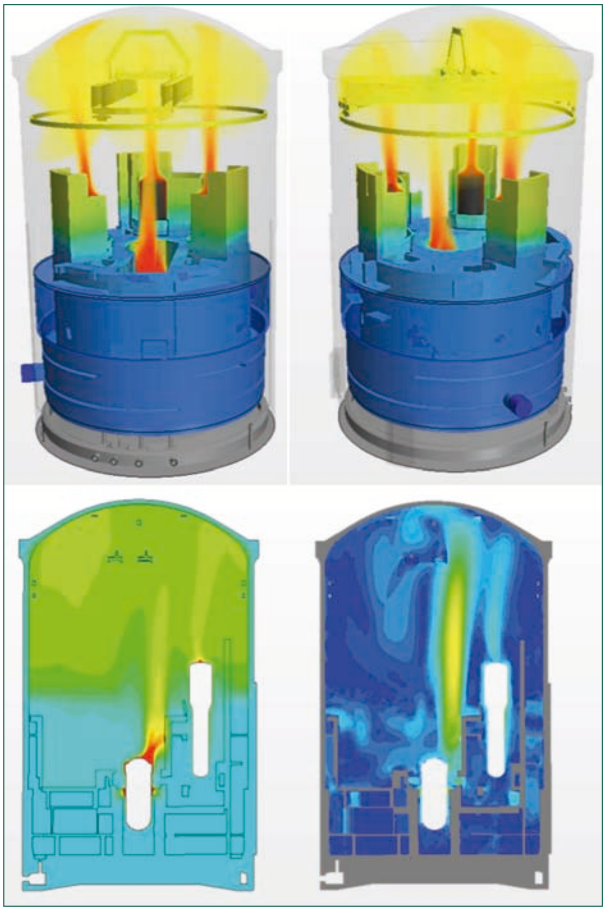

Figure 10. Temperature field in normal operation (blue: low temperatures, red: high temperatures).
Temperature field (left: vertical cut through the building) and velocity field (right, vertical cut through the building) in normal operation.

The use of a 3D CFD model in this case enables to better understand the thermal behavior of the building as a whole: hot plumes rise from the large components (Steal Generators –SG- and Reactor Pressure Vessel –RPV) and stratifies at the top of the building. Venting, though efficient, cannot completely prevent this behavior even in normal operation. Figure 9 and Figure 10 plot the temperature and velocity field inside the building in normal operation.

This deep and precise knowledge of the physics of the air motion inside the building enables FRAMATOME to propose adapted and customized solutions for the improvement of the ambient conditions inside the reactor building with a direct gain in terms of shutdown duration and availability of the plants.

Such a model has also been used to describe accurately accidental conditions, enabling to limit the amount of modifications required to demonstrate safe operation.

4. A WORD ON COMPUTATION TIME

3D CFD can provide margins for industrial cases. Nevertheless, these methods are based on the accurate representation of the physics and require a fine discretization of both time and space. This means that the computational resources to get results can be very high.

In order to be in line with projects planning, CFD analysts must master the computational time. A shortened computational time also enables to perform sensitivity analyses which are required to demonstrate the robustness of the method used. As a matter of fact, sensitivity studies to mesh density, time step and/or model parameters such as turbulent intensity etc.... are progressively becoming a standard for nuclear industry worldwide.

There are several solutions to master computation time:

- Optimize mesh density to just suit what is needed. FRAMATOME performs this by relying on sensitivity analyses performed at validation stage.
- Heavily parallelize the computation. This requires an investment in CPUs that can prove to be useful. Industrial should nevertheless be aware that this has a limit when dealing with very long transients as scalability of CFD codes, though very high, has its limits.
- Rely on fast mathematical algorithms for equations solving. CFD code vendors continuously work on this field, which is why FRAMATOME made the choice of using commercial CFD codes STAR-CCM+ and Fluent. It is important to notice that Lattice Boltzmann methods are also becoming more and more industrial and could bring large benefits to the sector.
- Develop engineering methods that enable a fast execution of codes. FRAMATOME puts its experience in the field at the service of its customer

5. CONCLUSION

3D methods and CFD in particular can help nuclear utilities in gaining margins for their safety demonstration for aggressions. Beyond the pure demonstration of margins, the intimate knowledge of the physics provided by 3D methods enables designers and utility to optimize their industrial tool and to design adapted and efficient solutions.

A few examples have been presented in this article, ranging from fire to thermal optimization of buildings. A lot more are produced and computational methods are being standardized.

In order to be licensable, 3D methods should be performed rigorously and must rely on a proper validation based on experimental data. It is also highly recommended to demonstrate the robustness of the computational method through several sensitivities.

All of this is possible only with a reasonable turn amount time for simulation. Even if brute force is always a plus, a real know how has developed to optimize computation time and detailed analyses on large buildings and/or equipment is now within reach.

REFERENCE

[1]. Fire safety journal – Special issue on PRISME – Fire Safety in Nuclear facilities (L. Audoin and J.L Torero), volume 62, part B – November 2013.