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Science of nuclear safety post-Fukushima

Conclusion

On open problems, from a scientific viewpoint, in the context of the European Union and in a world perspective

The extension of the present analysis could involve the following three themes:

1: *Decontamination completed, wholly demolished and greenfield open to visitors*: Can we ensure that the sites of civilian nuclear facilities can all be reduced to a state of free use for both soils, basements that groundwater? How can we be explicit in the detailed specifications, and make the demonstration on a typical case? How can we execute this plan in practice? Where are the obstacles in science and technology?
2: *Waste*: For all categories of radioactive waste, it is required that the demand for disposal of these materials corresponds well to the availability of space. The two do not necessarily coincide. We must therefore save time and space, and have **transient storage**, each type being adapted to a specific category of waste. The specifications of the equipment storage, and of the handling and transportation equipment associated, remains to be defined. It should then be demonstrated on a **down scaled model**, addressing the questions of mass flow, heat flow, radioactive decay and acceptable residual power, etc.
3: *Safety, security and malignancy*: The safety of the fuel cycle of nuclear power in France implies knowledge from a wide range of scientific disciplines. Among these, material science[1] is crucial and may be privileged. The malignancy against our civilian nuclear facilities is also a concern. Precedents in the U.S. were identified by Charles Perrow (Charles Perrow, The Next Disaster Reducing our Vulnerabilities to Natural, Industrial, and Terrorist Disasters, Princeton University Press, 2007).[2]

Whatever the energy context might be, is it not important to move forward towards the resolution of these three questions and thereby keep the civil nuclear option open for France, i.e. the choice of electricity independent of the downturns of world policy?

What are the scientific bottlenecks preventing progression in solving these issues of civilian nuclear power?

And among them, which ones can be reviewed by the Academy of Sciences? What should one do in France on this subject?

[1] The development of equipment structures (such as reactor vessels, the fuel cladding, the internal structures of reactors, etc.) requires **extrapolations** of the mechanical properties of materials beyond laboratory experiments, often limited in their duration. Then the non-linearities of the thermodynamic behavior and mechanics of materials based on the strain and effort on materials need to be taken into account. The question of the behavior of materials under irradiation (in particular the mechanical behavior of structural materials) results from three levels of physical phenomena:

(1) The genesis of point defects by irradiation, in particular by neutron irradiation. This damage at the atomic level can also have a chemical component, and lead by migration of defects created by the effects of segregation (especially at the grain boundaries). The genesis of radiation defects is usually a mechanism with a threshold neutron energy, but it has a linear behavior with the dose and flux.

(2) The dynamics of evolution of point defects to create clusters (tetrahedra of stacking faults, dislocation loops, cavities and bubbles). These processes can be seen as a sort of “chemical reaction between point defects and defect clusters”. The resulting behavior (number and size of clusters) is not linear in time and dose. One can have the effect of saturation, where the size or density of defect clusters no longer changes with time, in a sort of “dynamic equilibrium”.

(3) The relationship between defect clusters created by irradiation, and the macroscopic properties such as yield strength, work hardening rate, toughness... The relationship between defect clusters and the yield strength varies as the square root of the size of the clusters and their number per unit volume. One can have a linearity between the deformation and creep strain and dose (irradiation creep, essentially athermal) but it is more the exception than the rule. This shows that the macroscopic mechanical behavior of structural materials is generally a non-linear function of dose and flux, and secondly that it often depends crucially on the chemistry of the material and its evolution under irradiation. This explains why it is so difficult to predict the aging of components in power plants, why the option to extend up to 60 years requires many experimental studies, and why is the choice of materials in nuclear power is all the more conservative when the component one is closer to radiation source (Communication Yves Brechet, January 6, 2011).

[2] A first book by the same author was published in 1984 and since reprinted in 2007.

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Science

In addition to medical considerations mentioned in the Foreword to this issue, one may wonder on the value of the "**metric**" for comparing impacts with fatal or morbid consequences?[3] How to compare the impact of a crisis in the power plant itself (and vis-à-vis the staff and the public concerned) rather than the impact of the earthquake, the tsunami, but also to accidents in chemical plants, the space shuttle, coal mines, etc. The dose based metric (health, Sievert and radio toxicity) or those based on fundamental physics (radioactivity or landslide), are not always consistent. We escape from the incoherency sometimes talking risk, or probability.

How to deal with **uncertainties**? Those involving physical measurements concern the values of physical constants used. However, many uncertainties depend on the choice of a particular metric to compare policies or strategies. Therefore, we have both uncertainties of knowledge and uncertainty of methods (so-called structural uncertainty). What are the appropriate **indicators** for safety? Qualitative comparisons and/or quantitative metrics?

The intrinsic safety (i.e. without intervention of the control-command) of nuclear reactors is obtained by a **dynamic counter-reaction** linking three successive phenomena:

(1) **Changes in responsiveness** of the core of a reactor following a change of **reactivity** lead to variations of the **neutron flux** at each point of the heart of the reactor considered. This is a "neutronic" phenomenon. This neutron flux is translated into heat power dissipated in the core.

(2) **Changes in local thermal inputs** in the core, lead to variations in temperature, pressure, mass density, state of phases for the coolant, the fuel,[4] the cladding,[5] and also to gradients of physical quantities, and so to stresses and mechanical deformation, etc. in the core. This is the **thermodynamics** aspect of the problem.

(3) The variations of temperature, mass density, phase, etc. cause the **variation of the mean free**[6] **path of neutrons**, and hence the responsiveness of the heart to each party concerned. It is the **formation of reactivity controlled by the distribution of nuclei in the core** that provides the relationship between thermal and neutron physics aspects. The reactor cores are designed such that a positive fluctuation of responsiveness leads, by these three successive consequences, to a dissipation, allowing one to damp the primordial fluctuations. The ratio of these two quantities is called the coefficient

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[3] Examples of metrics are for Geoscience:

- the "Global Radiative Forcing-RF" "Adjusted Forcing-AF" by including fast counter-reactions ("feedback"), summed over a given period (e.g., from the beginning of the industrial era);
- the "Global temperature Change Potential-GTP";
- "Global Warming Potential-GDP";
- the sea level;
- the Richter scale;
- the temperature rise overall surface of the continents and oceans, etc.

Metrics are also used to compare risks. Note that the probability of events far from their mean value, were studied by Varadhan, Courant Institute, New York University, USA.

[4] The main phases created in the fuel by the irradiation and the temperature are:

- 1: rare gases (13.8% in mass of the fission product: xenon, krypton) and other gaseous phases;
- 2: metallic inclusion of technetium, ruthenium, rhodium, palladium, silver, cadmium, antinomy, molybdenum (9.6% in mass);
- 3: oxide inclusions of strontium, barium, cerium; zirconium (10.4% in mass);
- 4: in solution in the uranium oxide: Yttrium, cerium, neodymium, lanthanum, praseodymium, promethium, samarium, europium, gadolinium;
- 5 "volatiles": (14% in mass) cesium, rubidium, tellurium, iodine;
- 6: chemical component of metallic actinides and platinoids (see Henri Bailly, Denise Ménessier, Claude Prunier (Eds.), The nuclear fuel of pressurized water reactors and fast reactors; design and behavior, Collection du Commissariat à l'énergie atomique, 1999; p. 126) and for the ruthenium complex chemistry, the recent thesis (François Mousset, Électro-volatilisation du rhuténium en milieu nitrique, Thèse de doctorat de l'Université Pierre et Marie Curie, septembre 2010).

[5] The maximum external cladding temperature is about 350 °C in a PWR. The UO_2 pellet surface temperature is between 510 °C and 540 °C for a central temperature of about 920–1250 °C. These different temperatures create different pressures which build mechanical, thermal dilatation gradients, and then strain and stresses, which destroy the fuel materials (intrinsically brittle) into small fragments and chips. All these gradients versus thermal conductivity and diffusion, induce transport of these phases and of thermal energy, and also chemical reactions (see Henri Bailly, Denise Ménessier, Claude Prunier (Eds.), The nuclear fuel of pressurized water reactors and fast reactors; design and behavior, Collection du Commissariat à l'énergie atomique, 1999, p. 332 and Robert Guillaumont: personal communication, 2012). Roughly speaking, everything is in movement during irradiation, in the fuel pellets, including the just created plutonium (Bailly et al., idem, p. 104: §3.2. Plutonium redistribution).

[6] In the core of a nuclear reactor, the average half-life time of a neutron from birth in a fission and absorption is below a millisecond in the case of a "thermalized" neutron reactor. For a free neutron, the nuclear disintegration reaction is: neutron $\rightarrow$ proton + electron + antineutrino (electronic). The kinetic energy of this electron goes from zero to 0.78 MeV. In this β reaction, a weak interaction, the remaining energy, is carried away by the antineutrino. The neutron is stable, if it is combined with protons and other neutrons in the nucleus of an atom. The experimental and theoretical study of this nuclear reaction, of which the formulation of the initial and final states is apparently so simple, is actually very complicated. "The study of the half life of a free neutron make accessible roughly twenty observables of high energy physics, the synthesis of nucleus in the stars (astrophysics and cosmology), the half life of different β decays, etc. They contribute to knowledge about the interaction studies involving quarks and leptons simultaneously. They are used to test assumptions of phenomena beyond the Standard Model. In addition, experimental methods, increasingly refined, lead to new values of the half life of the neutrons, decreasing from 1100 ± 160 s to 885.2 ± 0.8 s" (pp. 1140–1146 of Dirk Dubbers, Michael Schmidt, The neutron and its role in cosmology and particle physics, Reviews of Modern Physics 83 (October–December 2011) 1111–1171).

of reactivity. In the five contributions of this special issue, the reactors have a design that makes the reactivity coefficient negative, thus **stable**.

It is nevertheless also necessary that the counter-reactions ((1) + (2) + (3)) does not change the nature of the physico-chemical phenomena that contribute to it (for example, a phase change of the fluid coolant or a chemical reaction between components of the heart, inflammation of sodium in contact with an oxidant). To satisfy this nullifying condition, it is important to consider in what circumstances these three links in the safety of a core, are linear with respect to the initial fluctuations. For the first link, the neutron, this linearity is discussed below.

The **linearity** of phenomena of neutron scattering, capture, fission as a function of **neutron flux and fluence**, when it comes to fissile material placed in the reactor, has allowed physicists and engineers to decouple the various physical phenomena. This decoupling has permitted them to develop the technology, both for the reactor and for the fuel cycle (mechanical, chemical, physico chemical separations, exploitation operations). This decoupling allows one to study and to develop **separately** these different aspects. This facility disappears when one consider the process resulting from multiple captures and decays, because it involves the products of fluence, of half-lives of radionuclides, so non-linearities appear and this implies having to make full-scale experiments. Among the consequences, there are also thresholds above which the phenomena are accelerating. This is the case for residual powers of α and spontaneous fission, but also for possible phase changes of materials used in the core. Hence, all the technical problems of development and operation that had to be taken into account in these new concepts (since their inception over half a century ago, in the United States, the United Kingdom, Russia, France, Japan, etc.). The most effective degree of freedom to destroy a particular isotope, is the fluence (neutrons/meter^2). However, the neutron flux is limited by **the thermal power density that can be extracted from the core**. The only remaining degrees of freedom are the irradiation time and dilution. For the former, it means the paradox that the durations have to be as short as 90 days. However, this is inconsistent with the constraints of energy production and non-proliferation.[7] For the second, this leads to more than half a century needed to destroy the stock of materials, with the unloading, chemical separations, re-manufacturing, handling, washing, etc.

On the scale of severity of accidents and incidents, in space, in time, in the intensity of impacts (with non-linearity that characterize them), we must oppose the fixed thresholds of natural phenomena such as phase changes, the “criticality” of an amount by weight of the materials, the limits of conduction, convection by the natural gravity, etc. One must not forget the thresholds associated with current capabilities of humans in technology.

One should also keep in mind that accidents due to non-nuclear materials can also impact the nuclear industry, as, for instance, the use of chemically reactive substances such as sodium.

Since human activities can never exclude the occurrence of an accident, even if its likelihood is small, this demands, for nuclear activities, an absolute confinement of harmful radioactivity in all circumstances including several decades after a full meltdown.

Methods of work

Comparing the impacts, also means **confronting the scientific exploration of phenomena and the world of public debate**. What do we learn from the past concerning this real issue? One may wonder if the classical method (based on synthetic reports on the basic sciences, where the claims are justified by references to publications in international scientific journals with a strict “referee” procedure) is appropriate here. Some economists do not think so and they propose to add other channels. “**How does science compare to public debate?**”

We have seen in this article a number of technical solutions, technical training, technical instructions, technical answers, etc. to facts which were not foreseen. Another human perspective, as noted by Charles Perrow (op. cit.), from an analysis drawn from most of the major accidents[8] affecting large systems of science and technology (which are by construction complicated, redundant and combine many categories of stakeholder), is though **the management of these systems**.

The scientific concerns mentioned above are partially shared by our European neighbors, Germany, United Kingdom, Belgium. What action could we take in common to address these scientific challenges? (i.e. 1: for the sheaths and cladding of the fuel elements, spent fuel containers, cask, canister, sealing, package, corrosion, welds, crimps and sealing, etc., **materials science** is crucial and may be privileged; 2: Perform the dismantling and return to free use and greenfield visit, of one of the first PWR reactors reaching the end of its life cycle, as a national test under the supervision of an appropriately designed specific authority.)

The satisfactoriness of the status of nuclear safety organizations in France has largely relied on a single design for the reactors, permitting the simple of uniform guidelines. In the future, one should pay attention to the “complexification” due to new designs.

[7] See in the report of the Royal Society, Fuel cycle stewardship in a nuclear renaissance, October 2011 (Chapter 4: The proliferation resistance of spent fuel management), p. 29.

[8] Accidents the U.S. space shuttle, high speed trains, aircraft, surveys oil tankers, mines, dams, tunnels, buses, chemical plants (including refineries, etc.), and so on, are in this category.

Human resources

All the above results imply:

- A strong and continuing commitment to basic science to reduce both the risks, the impacts, vulnerability and resilience of nuclear facilities;
- Vigilance of staff concerned;
- An effort to choose at all times as the best available practices;
- A increased action for university based of nuclear science and engineering.

How to implement these guidelines in France?

Besides the excellent results concerning the safety in the French civil nuclear electrical industry, thanks to the operators, to the control of the relevant public authorities and the expertise on which they rely, should not one create a unified scientific guidance in matters of safety, of **security**, of protection against radiations for the whole set of nuclear activities, both civil and defense related?

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