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Science of nuclear safety post-Fukushima

Foreword

The situation of nuclear energy today

Some preliminary observations seem necessary to introduce this special issue of the Proceedings of the Academy of Sciences series "Physics" (C. R. Physique) on the evolution of knowledge due to the recent events.

1) *The time scale*. Civil nuclear energy production systems must be strictly controlled, measured, monitored, not only during the period of 30 to 40 years of energy production, but also for the 40 to 80 years that follow. This must be ensured regardless of the weather, natural disasters, political developments or activity of hostile groups. This applies to both reactors for fuel assemblies and all nuclear facilities. We must also secure the process of intervention to protect populations and individuals.
   Risks compared. Can we prioritize the risks of the various technologies implemented in nuclear power? Can we compare the risks of civilian nuclear energy and those of other means of energy production? To do this, we would need to take into account the public, staff, people involved in installations, and that on multiple time scales. Tests of quantitative analysis through the assignment of probabilities have proved illusory. More than half a century of experience has highlighted the singular nature of the consequences of nuclear accidents of various kinds: induced reactivity, phase transitions, chemical reactions leading to fire, blast, explosion, neglect or obliviousness of radioactive materials, corrosion and breach of sealing, etc. On the other hand the incidents occurring during the exploitation of civil nuclear installations have their analogs with those of other large technological installations. Moreover, for very complex systems, the major crises caused by mechanical failure, wrong software or for ignoring a warning signal, are in fact errors of the "management" that has failed to take them into account.
2) *Complexity*. For large complex systems, such as those of civilian nuclear power, the most serious accidents are often related to the coupling, to the interference, of multiple simultaneous failures. We must therefore strive to decouple the components of the most dangerous elements.
3) *The fuel cycle of nuclear power* is a crossroads of potential risks: radioactivity, decay heat of spent fuel, the masses involved, the opportunity opening for malicious attacks, are and will remain a concern as long as a permanent disposal in our country and our partners in the energy field is not in place.
4) *Proliferation and malignancy*. Developments in technology now make it possible to reduce the size of nuclear power facilities, i.e. by laser separation of ionized uranium metal gaseous alloys as well of molecular compound of uranium: SILEX – Separation of Isotopes by Laser Excitation – using UF6,[1] are allowing access to this form of energy to a growing number of countries. Although each nation can legitimately claim to produce civilian nuclear energy, and thus to control the fuel cycle, this situation increases the potential for harm from hostile groups or networks. The solution studied by the IAEA would be to place all the facilities of the nuclear power cycle, the processes involved, the materials used, under the international supervision of the UN or a global agency.[2] This will not happen as long as the major powers do not want it, but crises are changing minds. France has all the technical tools, all the knowledge to prepare for these compelling needs.
5) *Decommissioning of nuclear sites*. Can we clean the land used by nuclear facilities, reactors, chemical processing plants, waste storage sites, and return them for other use as well? The answer is positive as it has been done to the site of

[1] Laser separation of metal uranium: Atomic Vapor Laser Isotope Separation (AVLIS); its scientific feasibility had been proved at the Lawrence Livermore National Laboratory with a pilot installation. The molecular process SILEX is now named Global Laser Enrichment (GLE); A private company called GEH (General Electric Hitachi) operates a GLE test loop referred as "Global Nuclear Fuel's (GNF)", in Wilmington, North Carolina, USA. A permit to build a commercial plant on the same site has been applied for recently to the Nuclear Regulatory Commission. The SILVA process developed in France at the CEA/Saclay is a metal vapor process; it has also demonstrated its feasibility.

[2] An analysis of the necessary steps for containing proliferation with the present technologies is made in "Fuel cycle stewardship in a nuclear renaissance", The Royal Society, October 2011, Chapter 4.

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a nuclear plant in Britain and several others in the United States.[3] This was achieved at the cost of commitment and unwavering efforts in mobilizing resources, processes, equipment and personnel for several decades after the thirty or forty years of power plant operation. The final disposal of high radioactivity material remains to be done.

6) *Energy resources and fourth generation*. Almost 200 000 tons of depleted uranium,[4] the unused residue of simple enrichment operations related to the preparation of nuclear fuel, is currently stored at Tricastin.[5] Nevertheless, that depleted uranium can be “fertilized” and serve as fuel in the fourth generation reactors. Fissioning sixty tons of material per year, one could face the energy demand of France for hundreds of years or more. For this important option to remain open, it is essential that international research on fast breeders should be actively pursued.

Presentation of the contributions to the special issue

The expertise of the control agency for nuclear installations must be based on knowledge of the allowable operating limits for all equipment and on the phenomena which occur when one exceeds these thresholds. In particular, one must know the *different sources of radioactivity* that can, over time, overcome the various barriers (known as “in depth” protection). This equipment is so difficult to design, and to implement, under strict conditions of radiation protection of personnel, that it is often international companies which are able to implement them. The heaviest of them were designed and operated by the CEA (Commissariat à l’énergie atomique and alternative energy) in recent decades. Those who are still in operation are described in the article by *Philippe Billot*.

The operation of nuclear power plants since the beginning of maturity was based on emerging science and technology of pressurized water reactors. These have performed for three decades, progressing in many aspects of their operating processes and thus their equipment, while retaining the concept of the PWR (it is the same for airplanes, cars or trains, etc.). A detailed study is made by *Bertrand Barré*.

The developments which have happened to the nuclear power plant in Fukushima Dai Ichi, have led to detailed and rigorous review of nuclear power in France, taking into account new hypotheses on the events initiating accidents. This has led to proposals for processes, equipment, instructions, defense, crisis management and environmental protection. The results of this process are set out in the article by *Xavier Pouget-Abadie* on Complementary safety equipment. The Nuclear Safety Authority has drawn up instructions to operators that need to be implemented by the authorities concerned.

Nuclear power plants currently in operation in the world use nuclear reactions of fission chain with neutrons from the fission of the uranium-235 isotope. Part of the neutrons are captured by the 238 isotope of uranium which, by successive reactions, creates plutonium-239. The latter is added to the fission of U 235, about a half more. The scientific and technical feasibility of transforming most of the uranium 238 into plutonium-239 was demonstrated in recent decades by experiments in the USA, UK, USSR, France, Japan, China, India. Indeed, the energy spectrum of neutrons in the core of a reactor allow their absorption by uranium 238 in a kinetic energy close to that of their birth. The state of knowledge in this area is described in the article by *Francois Gauche*.

The feedback of the operation of nuclear power plants in France for four decades has accumulated a bundle of relevant knowledge about these plants. It has relied on experts, themselves formed by the comprehensive review of the past, relied on laboratory research in both science and technology, and through dedicated tools. In addition, the achievements and applications of this research are shared with other experts from the European Union. These experts have a constant dialogue with the operators of nuclear facilities in all categories. In addition, these experts are consulted by the Nuclear Safety Authority, in preparing its decisions. This vast area of activity is described in the article of *Jacques Repussard* and *Michel Schwarz*.

For all these activities related to nuclear power, the final criterion of selection for processes, equipment, concepts, operating instructions, etc., is to ensure that staff in these facilities and the population at large are not at risk for their health. International standards have been developed, based on observations that have been ongoing for six decades, compiled by independent scientific societies, (ICRP), the UN agencies (IAEA, Fuel Cycle Safety Standards[6]), the OECD (NEA), the European Union, and of course, since the beginning of nuclear power in France, by the CEA. This mission was stated in the definition of its objectives in 1945 by Frederic Joliot. This objective is currently shared with the Institute of Radiation Protection and Nuclear Safety (IRSN) (Alain Carpentier, L’accident majeur de Fukushima : Considérations sismiques, nucléaires et médicales, A. Carpentier, É.-É. Baulieu, É. Brézin, J. Friedel, EDP Sciences, 2012, pp. 45–82). The human consequences of the crisis of Kukushima PP had been analysed by a report of the “Académie des sciences”, published in March 2012.

[3] “AGR-Berkeley” and “Yankee Rowe PWR”, “Maine Yankee”, “Connecticut Yankee”, “Completed Decon, green field site open to visitors”.

[4] Uranium stored near the plant Tricastin contains about 99.7% of the isotope 238. This alone has a radioactivity of 40 becquerel/kilogram of uranium, or 8×10^9 becquerel, a total of 0.3 curie, which poses no health problems in terms of radioactivity. The health effects suffered by the pioneers of radioactivity, like Madame Curie, came from the handling of the ore, which also contained the descendants α and β decay by including radium-226, polonium-218 and so on, passing the radiation at 520 becquerel/kg of natural uranium in equilibrium with its descendants, in addition, of course to the radiation due to chemically separated elements. For example, radium-226 has an α half life of 1600 years. Once separated chemically, it is a powerful emitter radioactive α (kinetic energy of 4.8 MeV).

[5] This stock of depleted uranium is growing every year about 5–7000 tonnes, depending on the rate of enrichment required.

[6] Among a very large sets of radiation protection standards, we can quote the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (Preparedness and Response for a Nuclear or Radiological Emergency Safety Requirements Series No. GS-R-2, November 6, 2002) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2006) reports.

Moreover, "*the health risks of low-dose radiation are revisited since 2009 by three major changes from the situation of low dose risk research in Europe; 1: To mobilize synergies between national research and training low dose programs much beyond what has been done so far; 2: To mobilize synergies between all disciplines necessary to investigate the low dose scientific issues with a fresh mind, much behind what has been done so far; 3: To mobilize resources at European Union level in such a way as to clearly encourage the above two*". (Multidisciplinary European Low Dose Initiative; http://www.melodi-online.eu, 2012) and (the low-level nuclear threat: Science, 2 February 2012, page 5).

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