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Nuclear Power: The Low-Carbon Energy of the Future

I. Nuclear Power: an Energy Source Still in its Infancy

We sometimes read or hear that nuclear power is an energy of the past. How can such a gross error of assessment be made in the light of history?

The discovery of self-sustaining nuclear fission by a chain reaction dates back to 1938, less than a century ago. The world's first atomic pile, implemented in Chicago, will celebrate its 80th anniversary at the end of this year. The world's first nuclear power reactor produced its first kWhs in Idaho in December 1951. Finally, the first French nuclear power plant was that of Marcoule in the Rhone Valley in January 1956, 66 years ago.

What do these dates tell us compared to the millennia of domestication of fire and the use of animal, wind and marine energy? What do these decades tell us compared to the centuries since humanity began to use fossil fuels, with coal spearheading this revolution starting in the 18th century? Nuclear energy is, in fact, a very young energy that appears even today as a singular point in the long history of energy for humanity.

Barring a singular lack of understanding of the events, successes, failures, setbacks and stumbles that have marked nuclear research and industrialization, how can this great adventure be relegated to the past? Both powerful and complex, nuclear energy arouses all the more passion and fear that the physical concepts behind it are difficult to understand but for a great deal of effort and time. None of this is easily compatible with the contemporary world, paralyzed as it is by its fears and increasingly removed from scientific reasoning, this often explaining that. Nuclear energy, then, is a poorly understood energy rather than an energy of the past.

An ill-known energy which is at the early stages of its development. It is an extraordinary opportunity to have it at our disposal at the very time when humanity is creating an inexorable change in the climate due to the intense use of carbon-based resources, oil, coal and gas. What would be the prospects for a planet with more than eight billion inhabitants - ten billion in 2050 - that would have access only to intermittent and variable energy from the sun and the wind, along with hydraulic energy, which is certainly dispatchable and sustainable, but has limited potential[1]?

Indeed, its assets are undeniable: nuclear power is capable of generating considerable amounts of energy - far more than the energy produced by fossil fuels – an energy that is entirely carbon-free and dispatchable.

Currently, nuclear power accounts for barely 4.3% of global energy consumption[2]. Fossil fuels (oil, coal and natural gas) account for nearly 82%[3]. These figures, which are staggering in the face of predicted shortages, are indicative of the extent of the task facing a country liable to resort massively to nuclear power.

Indeed, the physical reality is compelling: eight billion human beings will not be able to live, or even survive, off the energy of the sun and the wind alone. The orders of magnitude are just not there[4]. Most of those who have seriously studied the issue of our energy supply, caught between the exigency of climate change and the decline of fossil fuels, agree: in the current state of scientific and technical knowledge, nuclear energy is the solution[5] because it is the only one of all known energies to have the right orders of magnitude. Nuclear fusion energy could perhaps someday become the great sustainable future of nuclear energy, equal to the challenge. But its industrial development[6], if it is to happen, will at best take place in the next century, that is to say, well after the emergencies we have to face today and in the decades immediately ahead.

As nuclear power is still in its early stages, the question is how to bring it to maturity. How to bring nuclear power as we know it today to a level of perennial development, in other words make it

1 We do not mention, here, even more limited sources of energy such as biomass, geothermal energy and ocean power. As for hydrogen, it is an energy vector, not a source of energy.

2 Nuclear power accounts for 10.1% of the world's electricity production.

3 See IEA – Key World Energy Statistics - 2021

4 *Sustainable Energy – Without the Hot Air* by David J.C. MacKay – 2009 page 103. https://www.withouthotair.com

5 *Without nuclear power, the world's climate challenge will get a whole lot harder* Opinion by Fatih Birol and Rafael Mariano Grossi from the IEA published on CNN on October 9, 2020. https://edition.cnn.com/2020/10/09/opinions/without-nuclear-power-the-worlds-climate-challenge-birol-grossi

6 Remember that ITER is an experimental fusion installation aimed at producing energy for a sufficient duration but that that energy will not be converted to electricity. ITER is not aimed at producing an industrial prototype. See page 8 of this document.

"sustainable", on the scale of our planet as a whole. This means that in its development, it must seek to use the primary resource sparingly and to produce minimal amounts of waste.

The belief that nuclear power is an energy of the past - a poisonous ingredient of political environmentalist ideology? - is conducive to two disasters in which we have allowed ourselves to be trapped in France: on the one hand, the cessation of the R&D necessary for sustainable nuclear energy, and on the other hand, the loss of attractiveness of the discipline for young talent. Despite their being essential in view of climate and energy requirements, research for sustainable nuclear energy and the training of high-level scientists and engineers have been stopped dead.

A few reminders given below will help better understand the challenge of sustainable nuclear energy, and how important it is to restore scientific competence and the capacity to lead the nuclear research that the country needs urgently.

II. Mature Nuclear Energy: Sustainable Nuclear Power

As it operates today, nuclear power is not sustainable. Saving the resource and minimizing the waste were not the priority at the beginning of the nuclear adventure. Still today, we are exploiting fission energy with the technologies developed at the outset. If we were not mindful and did not change our ways, we would repeat with uranium the mistake that consisted in burning over two centuries, the fossil energy reserves accumulated over hundreds of millions of years. Uranium, like all of the Earth's natural resources, is in limited supply.

1. Brief overview of Uranium

Uranium is the heaviest atom present in the natural environment (Z = 92). Weakly radioactive and very long-lived[7], it is a fairly rare element, less abundant than copper, nickel or zinc, but 500 times more abundant than gold. It is present in rocks at a concentration of 1 to 3 g per metric ton and in sea water with much lower concentrations, 3 mg/t.

Uranium is made up of 99% uranium 238, less than 1% uranium 235 and traces of uranium 234. Only the uranium 235 isotope is fissile. Its only use is in nuclear fission applications, as it is the only nucleus on Earth capable of sustaining a chain reaction. Because of these unique characteristics, uranium is not well known by the general public or even by experts in fields other than nuclear energy. This explains the questions, the fears, and even the rejections that it arouses, like all things that are not well known.

It is in 1938, while bombarding uranium with neutrons and thinking they were about to find transuranics[8], that physicists discovered nuclear fission: uranium, against all expectations, broke up into two lighter elements. Since uranium has proportionally more neutrons than the two light nuclei produced, two to three neutrons are emitted during fission. The principle of the chain reaction was thus discovered less than a century ago.

7 4.5 billion years for uranium 238, ~700 million years for uranium 235, ~ 245,000 years for uranium 234.

8 Transuranics are elements heavier than uranium; these elements no longer exist in their natural state and are man-made, for example in nuclear reactors.

2. A considerable energy potential

When a uranium nucleus is fissioned, nuclear bonds are broken, unlike the combustion of coal or hydrocarbons, where chemical bonds are broken. The ratio of the amounts of energy recovered is of the order of a million. This explains why the fission of 1g of uranium produces as much heat as 1.7 metric ton of oil, or 2.8 metric tons of coal, or 1000 m^3 of gas[9].

The combustion of oil, coal or gas releases considerable quantities of greenhouse gases (GHG) including CO_2. The "ashes" of fission are the fission products (FP) and transuranics if no fast neutron reactors are available. There is no CO_2 emission since a nuclear link is broken and not a chemical link.

Uranium is thus a carbon-free energy resource, more than a million times more intense than carbon-based fossil resources. It is thus a highly strategic material. From the very beginning of nuclear power, there was a realization that with nuclear fission we had the key to energy supply for many centuries to come.

3. Making use of all the energy material contained in uranium

In France, as everywhere else, nuclear electricity production is based on the fission of uranium 235, which constitutes less than 1% of natural uranium. This leaves aside the bulk of the resource, uranium 238, which current reactors cannot fission, meaning that current nuclear production, while certainly a carbon-free source of electricity, wastes about 98% of the natural resource[10]. This was a good technological choice for the first stages of nuclear power, but it is insufficient for a mature development.

When a uranium-235 nucleus fissions under the impact of a neutron, it produces two smaller nuclei and a few neutrons. The neutrons produced by the fission are fast neutrons, regardless of the energy of the impacting neutron. Now, the slower the impacting neutron, the greater the probability that it will fission uranium 235, up to 200 times the probability of fissioning uranium 238. This is why, at the start of nuclear energy, the choice was made to favor the fission of uranium 235 as much as possible by slowing down the neutrons with a moderator, in this case water. Neutronic optimization led to the current technology of pressurized water reactors (PWR) with uranium 235-enriched[11] fuel. These reactors are called slow neutron reactors, or thermal reactors. In France, they are PWRs and EPRs.

Moreover, by design, slow neutron reactors favor the production of transuranics[12]. Transuranics are nuclei heavier than uranium, which are produced when uranium captures a neutron but does not fission; the slower the incident neutrons, the more probable such captures.

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9 The fission energy of 1 g of uranium is 7.2×10^{10} joules; the combustion of 1 metric ton of coal releases 3×10^{10} joules, that of 1 metric ton of oil 4.2×10^{10} joules, that of 1000 m^3 of natural gas 3.6×10^{10} joules.

10 In a slow neutron reactor, 2% of the uranium 238 is transmuted into plutonium 239, half of which fissions.

11 The fuel is said to be uranium235- enriched because in order to increase the number of fissions in the reactor, the uranium 235 content is increased well above its natural content, i.e. to 3 - 4%.

12 In the element classification terminology, these transuranics are "actinides": they belong to the family of 15 nuclei whose atomic number, or number of protons, is in the range Z=89, actinium, to Z=103, lawrencium.

With the current operation of nuclear fission, we are thus in the initial phase which has provided France with an extremely efficient and reliable nuclear power fleet of PWRs. But this utilization leaves aside most of the energy content of the product, uranium 238, and generates transuranics that can't be recycled in the slow neutron reactors, except for part of the plutonium 239[13].

That being said, ever since the beginning of this physics, we have been aware that it is possible to use the fission of uranium 238 provided the neutrons are not slowed down. The neutrons produced in a fission are fast neutrons. With these, the probability that fertile[14] nuclei such as uranium 238 or plutonium 240 will fission becomes very large.

In addition, since a fission caused by a fast neutron releases at least three neutrons, more new fissile nuclei by transmutation of fertile nuclei are produced in the reactor than are destroyed by fission or capture. It is this specific capacity of reactors operating with fast neutrons that is called breeding.

This feature, specific to the fast neutron reactor, makes it a remarkable tool for energy management: resource saving, since the production of energy from the same quantity of natural uranium is increased by a factor of 100, and waste reduction, thanks to the fission of the transuranics[15].

The fast neutron reactor is thus the instrument of mature nuclear power. It is where we need to go. It is a considerable asset that can provide the energy to meet the world's needs for carbon-free energy. Yet, as it is a key tool for the development of sustainable nuclear power, it very soon became the target of political ecologists who, after the French successes of Rapsodie and Phénix, never ceased to call for the shutdown of Superphénix, (obtained in 1997), and subsequently the abandonment of Astrid in 2019.

Note that fast neutron reactors (FNRs) are often put forward for their capability to burn the waste (the transplutonians[16]) produced in PWRs and EPRs. This is true, but it is very reductive and has led to loosing sight of the fact that they are first and foremost the most relevant fission technology to use all the uranium. This advantage comes from their ability, thanks to fast neutrons, to fission not only fissile but also fertile isotopes, either directly or after they have been transmuted into fissile isotopes.

The FNR is thus of great interest for the reduction of long-lived waste. The transplutonics recovered by recycling the spent fuel are mainly americium 241 (half-life 432 years) and americium 243 (half-life 7370 years) resulting from neutron captures on plutonium 242. Other elements result

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13 Spent fuel reprocessing operations in France allow the recycling of 15% of the fissile material, i.e. 15% of the 1% of natural uranium used.

14 A nucleus is said to be fertile if it transforms into a fissile nucleus after capturing a neutron; ^{238}U and ^{240}Pu for example, are fertile.

15 The transuranic (actinides) nuclei are large and, as a consequence, fragile. The larger these nuclei get via neutron capture, the easier it becomes to split them by fission under the impact of a fast neutron. Note also that large nuclei can fission spontaneously when they have an even number of protons and neutrons (e.g., californium 254 with Z=98; N=156 fissions spontaneously for nearly 99.7% of its decays).

16 Elements heavier than plutonium, also called minor actinides.

from neutron capture on the above nuclei, with transmutations into curium 242 (half-life 163 days), curium 244 (half-life 18 years), and plutonium 238 (half-life 88 years)[17]. By recycling these nuclei in an FNR, it is possible to fission them in large quantities. This, on the one hand, produces energy and, on the other hand, gives rise to fission products with much shorter half-lives. Thus, the multi-recycling of transplutonics in an FNR significantly reduces the quantity of transuranics present in the cycle, a significant change for waste disposal.

Certainly, it is true that today's nuclear waste, which contains fission products and minor actinides[18], is managed; they are separated from the spent fuel and then vitrified; they can be disposed of in a deep geological repository from which there will be no migration into the environment for hundreds of thousands of years. If scientifically and technically the solution is valid, it remains that having reactors that transmute and fission in situ most of these high-level and long-lived nuclei would be even more satisfactory!

One figure alone demonstrates the potential offered by the development of sustainable nuclear energy: with FNRs, France can boast of several millennia of energy autonomy based on its current stockpile of energy materials[19]. These, natural uranium and plutonium, come from the first decades of its scientific and industrial nuclear history. This stockpile corresponds to more than one thousand billion toe, or more than 10 million TWh...!

France's final energy demand in 2050 is estimated to be at least 130 Mtoe[20], or about 1300 TWh. This energy can be totally carbon-free only if most of it is electric. Obviously, the issue is no longer the supply of uranium, but the commissioning of fast neutron reactors, the only ones capable of using the uranium efficiently.

III. From the First Steps to Maturity: A Vital Need for Research

Since the first industrial tests in the 1950s, physicists understood the advantage of fast neutrons to fission 100% of the energy containing material (uranium 235, uranium 238, plutonium 239 and other transuranics), thus gaining a factor of 100 on the production of electricity, for the same amount of natural uranium used.

This is why research to develop these reactors was launched very early in France as well as throughout the world. After the rapid early successes, Rapsodie (1967), Phénix (1973), Superphénix (1985), the political ecologists, for whom sustainable nuclear power is a nightmare, worked hard at stopping this sector, and succeeded: the industrial prototype Superphénix was

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17 Traité de neutronique par Jean Bussac et Paul Reuss – Ed. Hermann - chapitre XXXII- 1985

18 "Minor" because the plutonium has been extracted.

19 Currently, France has more than 500,000 metric tons of depleted uranium and several hundred metric tons of plutonium, some of which is confined in spent fuel. The fission of 1 gram of uranium or plutonium releases an energy of about 2 toe. This gives the order of magnitude of the energy value of these materials: more than a thousand billion toe (to be compared with France's annual primary energy consumption, which is 250 million toe).

20 NegaTep – « Pour réduire les émissions de CO_2 de la France d'ici 2050-2060 » (*NegaToe – reducing France's CO2 emissions by 2050-2060*)- SLC 2021 – Ed. Les un-pertinents p.62. An earlier edition of NegaTep is available in English: *the Negatoe Scenario 2017* – see https://www.sauvonsleclimat.org/en/document-database/negatoe-scenario-2017-dividingbyfourtheco2emissionsfromfrance

shutdown in 1997, and the research prototype Astrid was discontinued in 2019. They have thus condemned not only the only dispatchable low-carbon energy solution that would allow the country to retain its independence, but also the indispensable research.

Meanwhile, Russia and China, but also the United States, Japan, Canada and the United Kingdom, have been advancing their R&D efforts, where France had long been one of the major leaders.

The ideologues that present nuclear energy as behind the times explain that there is no need for research since it is a past, even outdated energy. The inability to understand the need for research speaks volumes about their ignorance of this energy, of the physics behind it and of the prospects for its development. This is obviously very serious for a country like France, which was one of the cradles of this scientific adventure and which would be thus considered no longer in a position to take advantage of it, at the very moment when nuclear power is becoming the solution.

Indeed, the CEA, the French nuclear R&D organization that France was envied for throughout the world, has abandoned the preparation of the future of nuclear energy, its core area of activity. Worse, what little nuclear research is still being done there is aimed at "*not constructing the Astrid sodium fast neutron reactor demonstrator in the short term, while deploying a progressive strategy to prepare for the future, based in particular on fuel multi-recycling in the current 2nd and 3rd generation reactors* "[21].

Not only does the CEA stop the research on a prototype FNR explicitly called for under the law of 28 June 2006 on R&D for the management of radioactive materials and waste, but it also initiates R&D for multi-recycling in PWRs. This is absolute nonsense, since slow neutron reactors are physically incapable, as discussed above, of fissioning actinides: in PWRs, as recycling proceeds, the competition between fission and neutron capture is to the advantage of capture.

Thus, the multi-recycling of plutonium in PWRs leads inexorably to its transmutation into minor actinides, mainly americium, whose total increases in fine by 333%...! This mode of operation destroys the plutonium without taking advantage of its energy potential, and furthermore requires the consumption of uranium 235 in order not to smother the reactor. After 5 years of spent fuel storage, it appears that the amount of waste is multiplied by a factor of 3[22]. Multi-recycling in PWRs is a process that increases the consumption of the uranium 235 resource, and the production of radioactive waste, mainly americium.

The fact that this research program is included in the CEA's contract of objectives and performance with the State for the coming years, as a major research axis for the future of nuclear energy, is very disturbing. This is where the belief that nuclear power is behind the times, coupled with a profound ignorance of basic nuclear physics, leads us. The results in a few years, in economic, technological, environmental and ethical terms, will obviously be highly questionable and will be to the detriment of the credibility of the French nuclear industry.

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21 Contrat d’objectifs et de performances du CEA- 2021-2025; *CEA objectives and performances contract - 2021-2025*.

22 Internal CEA note for the dossier in response to article 51 of the PNGMDR (National plan for the management of radioactive materials and waste, drawn up under the aegis of the ASN in application of the law of June 28, 2006).

Unfortunately, this does not raise any particular emotion in political circles and at the highest level of the State where scientific expertise is no longer perceived as essential. Within nuclear institutions, qualified engineers are dismayed but silent; some have deserted. Yet we are at the strategic heart of the management of France's energy materials, both civilian and military...

This is all the more serious since the feasibility of research on FNRs was largely secured as, within the standards of the 2nd and 3rd generation, we went as far as the realization of the world's first large industrial fast neutron reactor prototype, Superphénix. The issue facing French research is thus to retrace its steps from 30 years ago, and to push further, to the level of the technological and safety requirements of the 21st century.

The transition from R&D to an industrial reactor takes two to three decades. France was in the lead until the early 2000s. Not only is it now lagging behind, but also it is lost in inappropriate research that no one is any longer able to evaluate correctly. Only the progress made by other major countries that master nuclear energy production shows, by contrast, the effort that would be necessary to resume the leadership in the R&D for sustainable nuclear energy.

The first steps in nuclear power were taken in the turmoil of the decades that followed the devastations of World War II. Reaching maturity aims to meet the world's needs for carbon-free energy; in France, it requires an urgent revival of R&D, targeting the real issues, without dispersing the efforts.

IV. Some Misconceptions or Illusions that Hinder Progress:

1 - Fusion is the future, let's wait

Numerous international experimental setups have allowed to come close to the minimum conditions of theoretical temperature, density and confinement time requirements for fusion. However, despite very encouraging results, the Lawson criterion, time x density x temperature of the reaction, remains at delusive values for energy production.

In the current state of research, the electrogenic use of fusion is not for tomorrow, nor for the day after tomorrow. Yet, climate change and the needs that result from it cannot wait until the next century or later.

2 - Nuclear fission with uranium is a thing of the past, thorium is the future

First, let us recall that in France we have hundreds of thousands of metric tons of uranium 238, whose colossal energy value we have seen. It would be absurd for France to turn to thorium, whose cycle is, in addition, not well-known. Naturally, countries such as India, which has an abundance of thorium, or China, which is using everything it can to meet its considerable needs, are interested in the corresponding research.

Natural thorium has only one isotope, thorium 232, which is not fissile; it cannot self-sustain a chain reaction. Its nuclear energy potential can be released via its transmutation into uranium 233, which is fissile. Thorium is analogous to uranium 238 with respect to fission.

However, the fission probability of uranium 233 under the impact of a slow neutron (PWR or EPR) is larger than the fission probability of uranium 235 (0.92 against 0.85). Moreover, during fission, it emits on average a few more neutrons than U235: 2.49 against 2.42. The product of the fission probability by the number of neutrons is an important neutronics parameter, noted η, called the "neutron reproduction factor". The neutron reproduction factor in a PWR, η, is thus 2.29 for uranium 233 against only 2.07 for uranium 235. What counts for the breeding process is how much larger η is than 2. It is 0.29 for uranium 233 versus 0.07 for uranium 235. This difference may seem small a priori, yet it is sufficient to produce, with uranium 233, more fissile material than is consumed, even in a slow neutron reactor. On the contrary, this is almost impossible with uranium 235 because the few excess neutrons are lost through sterile captures and neutron escapes from the reactor core.

This interesting alternative of thorium to the uranium cycle would first require the production of sufficient amounts of uranium 233, which would have to be recycled from spent fuel (just like plutonium 239 in the uranium cycle).

Despite this distinctive feature of uranium 233 fission in slow neutron reactors, the best neutron economy is still obtained with fast neutrons. Then the fission of fertile nuclei (thorium 232, uranium 238, plutonium 240...) contributes significantly to the neutron balance[23]. The low value of the capture cross sections[24] with fast neutrons reduces significantly the sterile capture of neutrons in the core materials[25].

Thus, in any event, the priority is to first develop fast neutron reactors in which either uranium238-plutonium239 or thorium232-uranium233 can be used as fuels depending on the material stocks available.

3 - There is largely enough uranium

Uranium reserves are estimated to be able to supply the world's existing fleet of slow neutron reactors for 90 to 130 years. This estimation depends on the price that is considered acceptable for uranium. Note that the 444 nuclear reactor world fleet[26] provides just over 4% of the world’s energy consumption.

However, to reason on these figures alone amounts to disregarding the evolution of the needs of carbon-free energy from now to the end of the century. Moreover, sticking to slow neutron reactors is tantamount to being satisfied with a squander that, on a global scale, poses a real ethical problem with regard to future generations.

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23 Balance of losses (capture, escape...) and productions (fission) of neutrons, obtained from the Boltzmann equation, the fundamental equation of neutronics. This equation links the neutron parameters (density, energy, position, velocity) and the parameters of the medium (cross sections of the different nuclei).

24 In nuclear or particle physics, the cross section is a physical quantity representing the probability of interaction or collision of a particle with another particle or nucleus or object of non-penetrable matter. It is homogeneous to an area. Its unit is the barn which is 10^{-24} cm^2.

25 « Traité de neutronique »(*Neutronics Manual)* Jean Bussac et Paul Reuss – Ed. Hermann – ch. XXXII

26 IAEA data as of 27 September 2021

4 - The price of uranium is still very low.

This assertion has been used constantly for decades to slow down FNR R&D; an assertion whose inconsistency can be appreciated today. Moreover, this argument would justify an unacceptable squandering of the resource. Finally, for those who insist on reasoning through economics, while it is first and foremost the reasoning of physics that should prevail, let us recall that: 1) the price of uranium argument is ambivalent, and predicting its evolution is, to say the least, uncertain, if not presumptuous; 2) at the dawn of the 21st century, as we are preparing to deploy nuclear power throughout the world, it seems less and less acceptable to use this argument to justify sticking with the technology of slow neutron reactors, which squanders the resource.

5 - Extracting uranium from sea water will be a possibility

This idea is quite dismaying, given the uranium content of seawater, but also the stockpiles of energy rich material already extracted, such as uranium 238. It amounts to saying that one would be ready to implement a disproportionate industrial enterprise-whose positive energy balance is far from certain-which would not be free of significant environmental damage, in order to squeeze a few micrograms of uranium per liter of seawater, while we have hundreds of thousands of tons of uranium sitting idle on French soil[27]!

To extract uranium from seawater is, to say the least, unrealistic, when we know how to produce fast-breeder reactors.

6 - The Small Modular Reactor (SMR) is the future of nuclear power

For some, the SMR marks a technological breakthrough, just like the generation 4 reactors. However, the SMR is not a technology change, but a small reactor as its name indicates; as a matter of fact, a large number have already been built, a proof that it is not a breakthrough[28]! An SMR, a reactor using uranium 235 and slow neutrons, remains a third-generation reactor at best, with no capacity for waste multi-recycling, as opposed to what can be read or heard here or there.

As it is currently being developed, because of a trend, but also because it can meet niche needs (very small territories, on-board reactors, reactors on a barge, reactors adapted to specific needs such as seawater desalination or hydrogen production), the SMR remains a slow neutron reactor and is thus not a sustainable nuclear tool.

On the other hand, a fast neutron SMR would be part of the FNR family, and because of its specific characteristics (modularity, moderate power, passive safety) would be a relevant development, for example to help make up for lost time in R&D. We could then

27 To obtain 1 metric ton of uranium, it would be necessary to process more than 300 billion m^3 of sea water. Remember that with current reactors, 65,000 metric tons of uranium are consumed per year in the world, corresponding to 4% of the world's energy consumption and 10% of its electricity consumption.

28 Hundreds of SMRs already exist (more than 400 at sea), and the current projects are all light water SMRs (slow neutrons), including those presented in recent proposals, allegedly for the future.

progressively move the French PWR and EPR fleet towards sustainable nuclear power. It could be wise, at each EDF site with EPRs to install fast SMRs, designed to manage the spent fuel from the EPRs. A (robotized) pilot fuel processing and fabrication facility for the SMR, also on-site, would be needed, another area of R&D to be undertaken without delay.

7 - The future is in molten salt reactors (MSRs)

Indeed, the concept is attractive, but its realization is still far off. These reactors in which the fissile material is "diluted" in a liquid medium, a molten salt, were tested in the United States in the early 1960s. The fuel being in liquid form can be extracted and recycled in a continuous process. Thus, the fission products can be removed and disposed of outside the reactor. The transuranics remain in the core until they fission and are thus completely "burned".

Thorium-232 and uranium-233 are the preferred fuel for the MSR, with a breeding possibility with any neutron spectrum, whether slow or fast, given the neutron dynamics specific to thorium (see item 2-thorium above). The reactor could be started with a load of plutonium 239 or of uranium enriched to about 15% uranium 235.

As with the FNR and thanks to the high temperatures accessible without pressurization, the thermodynamic efficiency is high (> 40%, compared to 33% for a pressurized water reactor).

Since the fuel is liquid, the quantity of fissile material in the reactor can be constantly adjusted. In case of an emergency, the fuel can be drained very quickly, an important safety advantage. Similarly, it is possible to extract fission products continuously, thus reducing the radioactive inventory.

Given these many qualities, the molten salt reactor is one of the 4th generation concepts. However, many problems remain to be solved in order to move from concept to realization. In particular, there are technological hurdles which will require large scale R&D concerning materials and salt chemistry (corrosion, high temperature, irradiation because the vessel is in direct contact with the fuel, precipitation phenomena, fission product management, salt treatment, etc.). In addition, thorium (n,2n) captures lead to the formation of uranium 232, with its radiation protection issues.

In the current state of research, in France[29] and abroad, the molten salt reactor is still at the "paper reactor" stage. Yet, the climate change issue and the resulting need for sustainable nuclear energy require that the first prototypes of 4th generation fast neutron reactors be developed as early as this decade.

This profusion of ideas in various directions, each more ambitious, original or risky than its counterpart, could well be another symptom of a discipline that has lost its footing, with no ability to sort and prioritize projects, and no strategy. Here again, the double penalty of stopping R&D and weakening the industry has largely contributed to this confusion.

29 In France, research on the MSR is led by the CNRS and focuses on a concept known as MSFR (Molten Salt Fast Reactor) which is a fast neutron version of the MSR.

Yet, for France, the time is lacking to spread thinly. The strategy for restarting the French nuclear industry will require to focus on what is still feasible, while France has to make up for several wasted decades; the sodium-cooled FNR has proven its value, as developed in the French laboratories and plants.

One of the lessons learned from recent years is that relegating nuclear energy to the past for want of familiarity with it is no longer acceptable. The result is that we are paying a high price in terms of our research performance, which is now lagging behind world research. Moreover, the collapse of our nuclear R&D, with scientifically ill-founded programs such as multi-recycling in PWRs, will not have escaped our former R&D partners abroad.

It is not surprising, then, that nuclear energy continues to lose its appeal to talented young scientists. The transmission of this discipline, at the heart of our understanding of matter, and the bearer of our energy future, is at a standstill, or worse, relaying impoverished or even erroneous content.

France needs to escape from this inability, in which it has placed itself, to project into the future. Restarting the dynamics where history began, i.e., in research, is probably the best solution.

Conclusion

It is probably no coincidence that those who consider that nuclear energy is an energy of the past are often the same ones who do not understand the absolute necessity of research, confusing it with innovation, which is only its by-product, and imagining that in nuclear matters it is possible to do advanced research in one's garage!

Those who speak of nuclear power in the past tense have understood neither its history, nor the most recent physics that emerged in the last century. In truth, we are only at the beginning of the development stage and, without an urgent resumption of research to develop a 4th generation FNR, nuclear power in France will end up being relegated to a parenthesis in its history of energy, one that has remained in its infancy.

There will be those fine minds who will argue, blasé of any ambition for the country, that we will buy from Russia, or China or America... The same will probably be emotionless when faced with the inexorable decline of our country's scientific and technological standing. The same will explain the inability of our industry to rebound. And we will end up getting used to our weakening with the successive energy, climatic and geopolitical shocks.

Finally, this absolute misconception about the place of nuclear power is a handicap to our future. How can we re-industrialize the country without efficient nuclear power? How, without R&D, can we reach the technological and industrial maturity of sustainable nuclear power? How, without the ambition and conviction of the young, can we succeed in reviving R&D and rebuilding the high-tech sectors that characterize nuclear power?

In order to turn towards the future, so essential to the fight against climate change, the only strategy would be to launch without delay a concerted research and industry development program, along two lines:

- on one hand, several dozen EPRs to renew the existing fleet and be able to satisfy the electricity demand which will at least double by the end of the century;
- on the other hand, a large scale R&D program led by scientists with recognized expertise whose mission will be to develop as rapidly as possible a prototype FNR that meets the 4^{th} generation safety requirements. This prototype will be developed along with the fuel reprocessing-fabrication demonstration unit, a necessity for the progressive transition of the French EPR fleet to sustainable nuclear power.

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