Jean-Paul BOUTTES

NUCLEAR WASTE: A COMPREHENSIVE APPROACH (4)

WASTE MANAGEMENT: THE ROLE AND COMPETENCIES OF THE STATE IN DEMOCRACIES

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SUMMARY

Different solutions exist for managing nuclear waste and protecting future generations over the very long term, though the difficulties encountered in implementing them should not be underestimated. These solutions require the existence of a State that is efficient and has the competencies to produce long-term prospective analyses to understand the issues facing the nuclear system, and the operational competencies to manage large-scale industrial projects like Cigeo. A look at the history of debates around nuclear waste in France also makes clear that the functioning of our democratic institutions needs to evolve considerably to better address this type of topic as well as complex subjects like climate change and biodiversity. These institutions must rely on scientific and technological expertise from different disciplines and be able to incorporate "prospective" and ethical resources in seeking to promote the general interest rather than the goals of partisans or activists. This is an invitation to invent new democratic institutions to reflect the major technical and industrial challenges that future generations will face.

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Jean-Paul BOUTTES

Engineer and economist. Formerly Senior Executive Vice President
of Strategy and Prospective and Chief Economist at EDF.
Former member of the World Energy Council Studies Committee
and Professor of Economics at École Polytechnique.

V. THE GOVERNMENT EFFICIENCY REQUIRED FOR WASTE MANAGEMENT TO BE SUCCESSFUL

As we have seen, solutions exist for managing nuclear waste, including ones that protect distant future generations from potential dangers over the very long term through geological disposal. Yet we should not underestimate the difficulties encountered in implementing solutions adapted to different categories of waste, as that implementation requires efficient States that can produce long-term prospective analyses to assess the issues facing the nuclear system and have the operational competencies to manage large-scale industrial projects like Cigeo.

Decisions about how to manage nuclear waste will be shaped first and foremost by the definition of an energy and nuclear strategy that is clear and consistent over time: whether to phase out or continue to use nuclear power over the next 50 to 100 years, and whether to recycle plutonium and depleted uranium. These choices will determine the types and quantities of waste produced, and therefore storage and disposal facility needs and capacities during all phases (production of appropriate matrices and containers, creation of storage facilities and geological repositories), which must be planned over several decades. France was a pioneer in opting for a closed cycle, involving the use of spent fuel, notably plutonium. But a series of decisions (and non-decisions) taken by the country in recent years has raised questions about what its strategy will be over the coming decades: anticipated shutdown by 2035 of 14 of the country's 900 MW reactors that recycle spent fuel, no commitment to a programme to build new EPR reactors that would in theory also be capable of using MOX fuels, and scrapping of the Astrid experimental reactor project, which undermined efforts to support the development of fast neutron reactor technology[1].

As regards the management of HLW and ILW-LL, no decision has been made as of today to move the Cigeo geological disposal project in Meuse/Haute-Marne to the operational and industrial phase. Governance of this project is currently complex, with many actors involved in decision-making and responsibilities dispersed, at a time when the focus should be on moving this 25-billion-euro industrial project forward with guarantees that it will be safe and completed on time and on budget. With an industrial project of this scale, one that requires oversight and logistics management over around 100 years, the strategy pursued must be clearly laid out and consistent over time, with industrial responsibilities clearly allocated to specific actors. This type of project serves as a reminder of what should be the roles and responsibilities of the State and public authorities in the management of public goods.

1. The need to once again have a nuclear and energy strategy that is clear and consistent over time

a) The uncertainty about waste management created by a series of recent decisions regarding the nuclear fleet and its evolution over the coming decades

The Multiyear Energy Plan (*programmation pluriannuelle de l'énergie - PPE*)[2] released by the French government in April 2020 reiterated the goal set in the country's energy and climate law of 8 November 2019 to reduce the share of nuclear energy in France's electricity mix to 50% (from about 75% currently). This decision, which the PPE correlates to forecasts calling for weak electricity demand in 2035, would lead to the closure by that date of 14 900 MW reactors, most of which play an important role in the recycling of spent

1. See ASN, Opinion 2020-AV-0363 [...] on studies to assess the management of radioactive waste and the recoverable nature of radioactive materials in application of the National Radioactive Materials and Waste Management Plan for 2016-2018, with a view to drafting the fifth National Radioactive Materials and Waste Management Plan, 8 October 2020 (www.asn.fr/content/download/172540/1775462?version=2). Also see Hearing of the National Assessment Board for research and studies into the management of radioactive materials and waste (CNE2), based on its opinion issued at the request of the Office, "Impact of the Covid-19 crisis on studies and research assessing the management of radioactive materials and waste", Senate, 25 March 2021 (www.senat.fr/compte-rendu-commissions/20210322/25032021.html#toc2), as well as the Public hearing, open to the press, on "Nuclear materials and waste: the case of depleted uranium", part of the study by Thomas Gassilloud, member of the National Assembly, and Stéphane Piednoir, member of the Senate, rapporteurs for the report "The consequences of stopping the Astrid nuclear reactor project", Senate, 3 December 2020 (www.senat.fr/compte-rendu-commissions/20201130/opecst_bul_2020_12_03.html).

2. Ministry of Ecological Transition, "French strategy for energy and climate. Multiyear Energy Plan, 2019-2023, 2024-2028", April 2020 (www.ecologie.gouv.fr/sites/default/files/20200422%20Programmation%20pluriannuelle%20de%20l%27e%CC%81nergie.pdf).

fuel since they are qualified to use MOX fuels. Because no decisions have been taken over the past decade to start building new EPRs, which would in theory be able to use MOX fuels, the possibility of using the 1,300 MW reactors is being studied. An analysis of safety margins could allow them to participate in mono-recycling, but this possibility would need to be studied and verified, and we are getting a rather late start if the goal is to be ready by 2025-2035 (*a priori* 2028 for the first 1,300 reactor using MOX). A similar observation can be made about the need to prepare for the storage of VLLW (mostly from the early dismantlement of the 900 MW units), quantities of which would increase considerably one or two decades earlier than previously thought. Volumes would be especially high knowing that French regulations classify as VLLW materials with a level of radioactivity considered negligible in all other countries (there is no "release threshold" in France, contrary to the rules applied in most of Europe today).

Moreover, the PPE officially ended the Astrid project, suggesting instead the exploration of multiple recycling in light water reactors, the industrial feasibility of which has not been established and the benefits of which are debatable. It also pushed back the deployment of fast reactors to the very long-term horizon, without laying out a credible research strategy or the arguments underpinning this shift: "France must continue to study the technological options that could ensure the complete closure of the fuel cycle over the long term (multiple recycling of spent fuels eventually enabling energy independence vis-à-vis natural uranium). To date, research efforts have focused on deploying Generation IV sodium-cooled fast breeder reactors (SFBRs). [...] However, since natural uranium resources will be abundant and available at low cost, at least through the second half of the 21st century, there is no need to press for a demonstrator and the deployment of SFBRs before this horizon. Research into SFBRs should thus shift to a new focus. Meanwhile, in the shorter term, multiple recycling in Generation III pressurised water reactors (PWRs) could help stabilise plutonium stockpiles, as well as spent fuel inventories, contrary to mono-recycling. The feasibility of this type of solution must thus be explored[3]".

Given the fragility of the option of multiple recycling in PWRs (MRPWRs) and the lack of credibility of the resources allocated to the ongoing FBR development programme, the ASN (in its opinion of 8 October 2020) questioned the management and status of spent MOX fuels, which are radioactive materials, as well as depleted uranium, both of which could be reclassified as waste if there were no credible options for using them going forward. The ASN estimated that, "at this stage, the safety of reactors and the safety of the facilities involved in the 'fuel cycle' as well as the radiation protection of workers have not been demonstrated for multiple recycling in

3. *Ibid.*, p. 144.

thermal neutron reactors[4]". As regards depleted uranium, the ASN noted that "projected volumes of depleted uranium use are not consistent with the quantities stored in France or projected production flows, and consumption of the entire stockpile of existing materials is unrealistic based on the recycling activities envisaged over the next century[5]". Lastly, as regards spent MOX fuel (or spent UOX) which are now not expected to be recycled in reactors before the very long term, the ASN "estimates that building additional storage capacity for spent fuel is a strategic requirement to ensure the overall safety of nuclear facilities[6]", and it recommends exploring dry storage solutions alongside the underwater solutions currently implemented in France.

Along the same lines as the ASN reaction, the CNE (in its annual assessment report of June 2021) indicated that "the 2020 Multiyear Energy Plan (PPE 2020) fundamentally changed the approach taken, at least through the end of the century. Alternative paths for managing materials and waste are proposed, but the uncertainties surrounding them remain great. Major technological barriers that need to be overcome have already been identified. The feasibility of implementing the aspects of the PPE 2020 related to the management of materials and waste has not been demonstrated for several of the guidelines[7]". The CNE summarises the questions posed by the new guidelines as follows: "Some of the new guidelines set forth in the PPE 2020 have a significant impact on the management of radioactive materials and waste. In particular, the postponement to the latter part of the century of the deployment of fast breeder reactors pushes back the full closure of the fuel cycle by as many years, while an intermediate step is introduced: the multiple recycling of plutonium in PWRs (MRPWR). Moreover, 14 900 MWe reactors will need to be shut down by 2035, which will make it necessary to use MOX fuel in 1,300 MWe reactors to limit the increase in the stockpile of spent UOX (uranium oxide) fuel. Lastly, decontaminating and dismantling the reactors that are shut down will produce large quantities of waste, notably VLLW, at a time when storage capacity for that category of waste is nearing saturation[8]".

In July of 2021, the rapporteurs for an OPECST report analysed the consequences of the scrapping of the Astrid nuclear reactor project. They "identified four key impacts of this decision:

– It creates doubt about the consistency of the strategy followed for the past 70 years to close the fuel cycle, and thus about France's long-term plans.

4. ASN, *op. cit*., p. 10.

5. *Ibid.*, p. 7.

6. *Ibid.*, p. 11.

7. CNE, "For research and studies into the management of radioactive waste and materials", assessment report No. 15, June 2021, p. 13 (https://cne2.fr/telechargements/RAPPORT_CNE2_15_2021.pdf).

8. *Ibid.*, p. 15.

The country could come to be seen as a relatively unreliable R&D partner. Moreover, the countries that want to purchase nuclear power plants and have long-term relationships with suppliers could wonder about France's intentions;

– Astrid was France's flagship nuclear R&D project. The industry was already having difficulties, and the scrapping of this project will make it harder to attract students to the field;

– In the absence of a unifying project, the knowledge acquired over 70 years of research into SFBRs could be lost;

– Over the longer term, the strategy for closing the fuel cycle could be abandoned, with potentially serious consequences for the French nuclear industry and the geological disposal of waste[9]".

In sum, three significant agencies – the ASN, CNE and OPECST – have all reacted negatively to recent developments in the area of materials and waste management.

b) Strategic questions around power plant needs, the nuclear technologies of the future, and the waste management issues raised by recent decisions

Beyond the planning and implementation challenges these decisions pose in terms of fuel cycle and waste management tools, it is necessary to discuss a few of the strategic questions they raise for France, questions that the documents drafted by public authorities and government agencies (DGEC, ASN, OPECST, CNE, Court of Auditors, etc.[10]) only address very partially.

Indeed, all recent decisions and guidelines create challenges in terms of waste management: not due to a lack of solutions – they exist, and can handle quantities that would result from different strategies (nuclear phased out or not, open cycle or closed or mono-recycling) – but because it will take time to conduct all the safety studies and identify all the technical options, to find storage or disposal sites while involving all stakeholders in the consultation and decision-making processes, to develop and bring together all the necessary industrial skills, and to build the matrices, packages and structures necessary. Every effort should be made to avoid changing course often. Yet it is easier to give in to that temptation when the guidelines set by public authorities are not established based on serious, robust and shared analyses of how the context could evolve over the next few decades.

9. Thomas Gassilloud, member of the National Assembly, and Stéphane Piednoir, Senator, "L'énergie nucléaire du futur et les conséquences de l'abandon du projet de réacteur nucléaire de 4e génération 'Astrid'", report prepared for the OPECST, 8 July 2021, National Assembly, Report No. 4331, p. 14 (www.assemblee-nationale.fr/dyn/15/rapports/ots/l15b4331_rapport-information).

10. See Court of Auditors, "L'aval du cycle du combustible nucléaire. Les matières et les déchets radioactifs, de la sortie du réacteur au stockage", 4 July 2019 (www.ccomptes.fr/system/files/2019-07/20190704-rapport-aval-cycle-combustible-nucleaire.pdf).

And recent choices also pose problems with regard to the real long-term energy and nuclear challenges France will face:

– What nuclear power capacity will it need over the coming decades as it deals with climate change, the need for dispatchable resources in the electricity mix, and geopolitical threats to security of the supply of fuel and key equipment?

– How well can it prioritise problems in terms of safety and radiation protection, and create regulations based on approaches that are coherent in terms of health and environmental impacts?

These questions deserve to be explored in much greater detail than what we offer below. Our high-level overview is meant solely to give an idea of the collective work that must be done, before waste management begins, to ensure that it can be implemented efficiently and safely over time.

The Multiyear Energy Plan and the shutdown of 14 nuclear reactors to reach the target of 50% of the electricity mix in 2035

The shutdown of France's 900 MW reactors, most of which are currently authorised to recycle MOX, is planned after a lifetime of around 50 years, implying decommissioning between 2029 and 2035. A study is being conducted on offsetting these closures by ensuring that a sufficient number of 1,300 MW reactors can use MOX. This modification would not happen before 2030 at the earliest, given the time required to make operational adjustments and secure authorisations. Using MOX fuel in 1,300 MW reactors is possible in principle, but it is necessary to take the time to conduct studies to guarantee that sufficient safety margins exist and that the mode of functioning of these plants does not need to be substantially modified to accommodate this new constraint.

The decision to shut down the 14 reactors was not taken based on technical constraints. The first round of fourth ten-year inspections of 900 MW reactors was completed in 2020. As required by French law, they involved very comprehensive inspections, sometimes substantial equipment replacements, and modifications to reflect feedback (particularly after Fukushima) and best available technologies. These upgrades are notably intended to reduce the risks associated with aggressions from fire, explosions, flooding or earthquakes and to improve the safety of spent fuel pools and the management of core meltdown accidents.

Since 2021, the ASN has validated the generic portion of the periodic reviews (every ten years) of 32 900 MW reactors, allowing their operating lifetime to be extended from 40 to 50 years[11]. It considers that the measures

11. See ASN, decision No. 2021-DC-0706, 23 February 2021 (www.asn.fr/l-asn-reglemente/bulletin-officiel-de-l-asn/installations-nucleaires/decisions-individuelles/decision-n-2021-dc-0706-de-l-asn-du-23-fevrier-2021).

planned will allow the safety of the 900 MW reactors to be brought into line with that of Generation III reactors. This initial phase of inspections will be followed by a compliance review, conducted separately for each individual reactor, through 2031. An extension of the operating lifetime to 60 years would thus be possible, given the significant work done as part of the "Grand Carénage" plant refit programme, provided that additional information is provided to ASN, notably about vessel performance. The United States is already extending the lifetime of the bulk of its nuclear power plants to 60 years (and even up to 80 years for some plants).

It is also clear that, if the Paris climate targets are to be taken seriously, we will need to rely massively on decarbonised electricity (nuclear and renewable), including for other uses such as mobility (electric vehicles) or the production of hydrogen for certain industrial processes or long-distance freight transport. Based on this outlook, electricity demand forecasts must be raised considerably on the 2030-2050 horizon. Having access to a reliable nuclear fleet (existing power plants that are part of the refit programme plus Generation III EPRs), producing electricity with no CO_2 and in a cost-efficient manner, would be particularly helpful in providing a significant share of base-load generation while offering major advantages in terms of dispatchability and flexibility to adapt production to consumption, supplementing intermittent renewable energy sources (which are not dispatchable).

Such an extension of the lifetime of the 900 MW reactors (subject to approval by the ASN), together with a commitment to build several EPRs that could be brought into service in 2035-2050, would incidentally make it easier for mono-recycling to continue.

Within this context, it should also be borne in mind that the waste reprocessing and vitrification plants in The Hague will need to be renewed toward 2040. These are unique and important skills that must be maintained over time if we are to continue to use civil nuclear power, both so that fast reactors remain an option over the long term and to master the vitrification technologies that are particularly useful in creating matrices that render the waste inert and prevent dispersion.

The consequences of scrapping the Astrid project: Can multiple recycling in light water reactors be a temporary alternative to fast breeder reactors?

With the Astrid project having been scrapped and the launch date for Generation IV fast reactors being pushed back farther into the future, multiple recycling in PWRs (MRPWRs) is now being considered. The aim is to use the plutonium obtained from the reprocessing of spent MOX, combined with depleted uranium, in order to limit the quantities of spent MOX fuel that need to be stored, to stabilise the stockpile of plutonium, and to reduce natural uranium needs.

It is important to point out two important distinctions between how neutrons react in slow neutron reactors cooled with water and in fast reactors cooled with sodium[12]:

– the first difference is that slow neutron reactors rely primarily on the fission of uranium 235, which makes up just 0.7% of natural uranium, whereas fast reactors rely mostly on the massive transformation of uranium 238 into plutonium 239 followed by the fission of the latter. This ability to also use all the uranium 238, which makes up 99.3% of natural uranium, increases resources by a factor of 100. In other words, slow neutron reactors only use about 0.5% of natural uranium to produce energy[13]. One could conceive of water reactors that make it possible to "harden" the spectrum of neutrons by adjusting several variables, for instance by reducing the moderator (the water that slows the neutrons in addition to acting as a coolant) relative to the fuel in order to slow the neutrons slightly less. These are called "high conversion" (HC) reactors, and boiling water reactors (BWRs) are undoubtedly better candidates than PWRs. Still in the exploratory phase for now, the technology would *a priori* only make it possible to use 1% of the natural uranium (twice as much as with the current solution)[14]. The targets that could be met with existing water reactors and those under construction, such as the EPRs, using specific fuels (which must notably get a "boost" of uranium enriched with uranium 235, which uses more of this scarce resource…) are even more limited: current mono-recycling (plutonium, with some of the depleted uranium from enrichment) allows a resource savings of about 10%[15]; a second recycling would only add a few percentage points, and the technology would not be ready before the end of the century;

– The second difference is that fast reactors are also capable of causing fission, to a certain degree, of even-numbered plutonium isotopes, and that fast neutrons are less subject to capture by the uranium or plutonium. These two interrelated characteristics allow them to limit the quantity of minor actinides and to maintain the isotopic properties of the plutonium (i.e. to limit the portion of even-numbered isotopes in the plutonium), which is not the case with slow neutron reactors: the inexorable increase in the share of even-numbered isotopes of plutonium, non-fissile in a slow neutron environment, is what makes it necessary to increase the percentage

12. To read more on these two topics, see the key reference book by Dominique Grenêche, *Histoire et techniques des réacteurs nucléaires et de leurs combustibles*, EDP Science, 2016, particularly chapters 4, 8, 13 and 14.

13. Natural uranium contains 0.7% uranium 235, but losses occur during enrichment (uranium 235 that is found in depleted uranium) and during "combustion", offset by the fission of a very small portion of uranium 238 via its transformation into plutonium 239.

14. See Dominique Grenêche and Michel Lecomte, "Optimisation de l'utilisation des ressources dans les réacteurs à eau légère", *Revue générale du nucléaire*, No. 5, September-October 2010, p. 28-38.

15. Knowing that the recycling of reprocessed uranium (URT) remaining after reprocessing of spent fuel can also result in an around 13% gain in resources.

of uranium 235 enrichment in the fuel, as a result of which the spent fuel left after the fuel is recycled several times in water reactors will produce waste with greater potential to be radiotoxic (more minor actinides). The gains in terms of the depth of geological disposal space required relative to mono-recycling should therefore *a priori* be limited.

Multiple recycling in existing water reactors is thus unlikely to result in significant gains relative to the mono-recycling in use today in terms of meeting the two primary goals: first, conserve uranium resources, the most important long-term objective, and second, reduce radiotoxicity and the space required for the disposal of long-lived waste. It should also be noted that, given the significantly increased presence of even-numbered isotopes of plutonium and minor actinides, the fuel cycle equipment to be developed will (in terms of fuel fabrication) need to have different characteristics than that intended for multiple recycling in fast reactors. In this regard, the solution offers benefits in terms of preparing for the future where reprocessing is concerned but is unlikely to have a decisive advantage over simply extending-renewing mono-recycling in The Hague, which will in theory enable the preservation of key skills in the areas of reprocessing, fuel fabrication and waste vitrification, as long as efforts are made to integrate useful technological innovations and to initiate research on the fast reactor cycle.

Recent public documents on multiple recycling in PWRs often cite its benefits in terms of stabilising stockpiles of spent MOX fuel and the inventory of plutonium in the fuel cycle. These objectives for the next few decades are somewhat surprising. Spent MOX fuel can easily be stored for a few more decades in a safe manner, as is done today, with volumes that will remain extremely low, while we wait for fast neutron technology to be mastered. Should the energy context change and the innovations available on that time horizon make it unnecessary to deploy fast reactors that can use the energy content from the plutonium in spent MOX fuel, there will still be time to place it in geological repositories with the right confinement properties for the very long term. As regards plutonium stockpiles, every effort must be made to prevent an increase in the inventory of separated plutonium that is weapons-grade, i.e. that has a high share of plutonium 239. In spent MOX fuel, plutonium 239 is not separated from other radioactive substances, including a high share of even-numbered isotopes of plutonium, making it unsuitable for military uses. Moreover, if mono-recycling continues over the next few decades, then the additional stockpiles of spent fuel in France will be low relative to the totality of spent fuel stored or disposed of worldwide.

Multiple recycling in existing water reactors thus does not make a meaningful contribution to managing uranium resources over the very long term or to reducing the capacity required in disposal facilities for long-lived waste. In addition, the objectives it is meant to promote do not hold any real benefits, and its implementation raises issues of safety and radiation protection for workers – issues that will need to be resolved, likely resulting in additional costs. If the only goal is to show that, should the deployment of rapid reactors be pushed back to the end of this century or the beginning of the next one, we can in the interim use a small portion of the spent MOX fuel and an even smaller share of the depleted uranium to prevent them from being classified as waste, then perhaps a more simple and direct alternative would be to set up a credible R&D strategy for developing fast reactors on this time horizon while planning for the necessary expansion (limited) of storage in the interim.

Looking past the Astrid project to create a credible research and development strategy for fast reactors

The main advantage of fast reactors is indeed the ability to increase resources by a factor of 100 by allowing the fission of uranium 238, not just uranium 235. This technology is thus a CO2-free energy option that could not only contribute to France's economic prosperity and security of supply over the very long term, but also contribute massively to the production of carbon-free electricity across the world over several centuries. These reactors can also burn even-numbered isotopes of plutonium and a portion of the minor actinides. Such characteristics make it possible to envisage mixed fleets of PWRs and FBRs, with recycling in FBRs restoring the isotopy in spent fuel from PWRs while limiting the actinide content in final waste. Access to FBR technology is therefore key if it can be mastered industrially with additional investment costs only exceeding those of PWRs by 20 to 30% at the most, with a long-term goal of reaching cost parity if possible. We would in that case have access to a source of carbon-free, dispatchable base-load electricity, one that could come to make up 10 to 30% (or more) of the global electricity mix (in countries that master the technology and have the institutions to properly verify safety and non-proliferation), knowing that electricity demand could double or treble by 2050-2100[16], and that a fleet comprised solely of PWRs and BWRs with installed capacity four to five times higher than existing nuclear would go through all identified reserves and uranium resources, which the IAEA estimates at around 15 million tonnes[17], in 60 years. Having access to fast reactors thus offers assurance against the risk of relying on uranium deposits with increasingly low uranium content, which could drive up extraction costs by a factor of 3 to 5 or possibly more (economic rather than physical scarcity). It could also be a way to avoid increasing mining activity to obtain the necessary uranium 235 (at a time when such activities are likely be

16. See IEA, *Energy Technology Perspectives 2020*, 2020 (report downloadable on www.iea.org/reports/ energy-technology-perspectives-2020).

17. See IAEA-NEA, *Uranium 2020. Resources, Production and Demand*, 2020 (www.oecd-nea.org/jcms/pl_52718/uranium-2020-resources-production-and-demand?details=true).

massively developed, for instance to extract certain critical materials and other materials needed for renewable energy sources) and avoid problems related to land use, landscapes, and biodiversity. It should also be noted that industrial and economic mastery of this technology, together with the existence of stockpiles of depleted uranium and plutonium (which can be mobilised by reprocessing fuel from light water reactors), would make it possible to ensure, over the very long term, a country's security of supply and energy independence. This explains the growing interest in this technology in countries like Russia, China and the United States.

The Astrid project, which was launched in 2010 with a goal of building a 600 MW SFBR, was designed in the 2000s, at a time when the "nuclear renaissance" was being prepared and uranium resources were expected to become scarce in 2040-2050. This may have made it seem urgent at the time to have a large-scale industrial demonstrator ready by 2020-2030. As we have seen, sodium technology has reached industrial scale, but only after the time was taken to comply with stricter safety standards in the wake of serious accidents involving core meltdowns, to achieve at least the same level of safety as with Generation III (including the post-Fukushima measures), either through enhanced "prevention" of the meltdown (to avoid it) or by "mitigation" of the consequences in the event of a partial melting of some fuel elements. From this standpoint, sodium-cooled fast reactors have some disadvantages vis-à-vis thermal neutron PWRs, due to the risk of the core reacting in the event of draining or if the sodium boils, and to challenges in using water to cool the vessel due to sodium-water interactions; it also has advantages given sodium's high thermal inertia. The goal is thus to simultaneously identify protections and strict safety standards that address these characteristics. The Astrid project made it possible to test interesting innovations, especially in the areas of backup core cooling systems, recovery of melted fuel, and the design of a large-scale "low void effect core" (CFV in French) that prevents the chain reaction from restarting in the event of a loss of liquid sodium. Yet the close deadline of 2020-2030 did not leave time to simplify the design and explore all possible avenues in terms of research into these safety issues: the starting point was thus a large, complex and therefore very expensive industrial demonstrator being prepared for a time horizon over which, with a "nuclear renaissance" that failed to materialise (low-cost fossil fuels over the past three decades, Fukushima accident, climate targets still perceived as far off in the distance, etc.), uranium resources would be abundant for a few extra decades. One can thus understand the hesitancy to start construction on an Astrid reactor that is too complex, and to do it quickly. On the other hand, one cannot help but note, as do the CNE and OPECST, the absence of a credible roadmap for 2030-2040 to develop a small research prototype (50-200 MW) and initiate in-depth studies on cost controls and safety concerns in the event of a serious accident. The way to gain this credibility is to explicitly list the avenues that need to be explored: large reactors such as Astrid, and small reactors (Advanced Small Modular Reactor, sodium SMRs), for which issues of criticality are known to be much easier to resolve below 200-250 MW (much more significant neutron leakage).

It will also be necessary to:

– Set up an organisation that allows scientists, industrial actors and safety specialists to work together during all key phases of the process, starting with design, with the same end-goals in terms of safety and cost controls and ensuring that the design is simple and robust. This organisation, and these shared goals, can guarantee that objectives are met with projects like these;

– Have a nuclear and energy strategy that is clearly expressed through policy, with open-ended long-term prospective analyses underpinning the justifications for these strategic choices;

– Indicate, for this fast reactor R&D strategy, the different milestones to be met (research loops, prototypes, related tools of the cycle and their translation into human and financial resources).

We find some of these relevant "words" in the CNE's 2021 report on planned work by the CEA on sodium SMR design (partly inspired by Astrid) and on participation in the European large sodium reactor project ESFR-SMART[18]. Yet actual "things", end-goals, objectives in terms of safety and costs, technical and scientific concepts of operation, and policy strategy are virtually absent, and the human and financial resources made available are not sufficient. The agency thus concludes: "The CNE notes that the resources allocated to this work, particularly financial, could only match a series of academic exercises without addressing the objective of developing a new reactor project. Moreover, no study on the related fuel cycle has been presented to the Commission[19]".

An ambitious and credible roadmap for developing sodium fast reactors, combined with continued mono-recycling in existing PWRs and then in Generation III reactors, would actually consent to consider spent MOX fuel and depleted uranium as useful materials for the future. It would also provide the visibility needed to prepare for the renewal of The Hague facilities, to plan the storage necessary for spent MOX and depleted uranium, and to lay the groundwork for a possible industrial deployment of SFBRs to complement PWRs. We would also add that the potential benefits of molten salt reactors could justify longer term research into that technology, the potentialities of which are in some regards complementary to sodium, though reaching maturity will take longer.

18. CNE, *op. cit.*, p. 16.
19. *Ibid*, p. 17.

Depleted uranium and very low-level waste

These two subjects – the ability to reuse depleted uranium[20] and the absence of a release threshold for VLLW in France – are less strategic than those discussed above, but they too illustrate how difficult it can be to clearly name and hierarchise problems (we could also have mentioned analogous subjects such as the management of LLW-LL or bituminous waste).

> **The recyclability of radioactive materials including depleted uranium**
>
> Radioactive substances include radioactive materials, for which a future use is planned or envisaged, and radioactive waste, for which no future use is planned or envisaged.
>
> Plans for managing radioactive substances over the long term will differ depending on whether they are classified as materials or waste. Since radioactive waste will not be reused, it requires a long-term storage solution, which is usually disposal, sometimes after an intermediate step (processing, packaging, storage).
>
> Materials that are to be recycled are stored until they are ready to be used. Requirements in terms of safety, radiation protection and environmental protection are the same whether radioactive substances are classified as materials or waste.

Depleted uranium (uranium 235 content of between 0.2 and 0.4%) results from the enrichment of natural uranium. As of today, it is not considered waste, and it is partially reused, either being enriched in the same way as natural uranium or used in MOX fuel. The full reuse of depleted uranium is envisaged as part of plans for Generation IV reactors (other uses are also possible in the industrial sector).

The depleted uranium that is not reused is stored in the form of a black powder that is stable, incombustible and noncorrosive. These physical properties make it suitable for transport and storage. It is less radioactive than natural uranium extracted from mines. Depleted uranium is stored at facilities in Tricastin and Bessines, in warehouses of nearly 35,000m² storing about 350,000t (i.e. storage space that takes up less than 200 x 200 m to store sufficient energy resources to power the country for centuries).

The ASN estimates that "the valorisation of a radioactive material could be considered to be plausible if the existence of an industrial route is realistic within a timeframe of about 30 years[21]". Beyond that timeframe, it is necessary to anticipate storage needs over corresponding time periods, longer than about 30 years, in safe conditions, along with the possible management of the radioactive substance as waste.

20. See the ASN opinion of 8 October 2021. Also see the minutes of the OPECST public hearing, "Matières et déchets nucléaires : le cas de l'uranium appauvri", 3 December 2020 (annex to the abovementioned OPECST report, "L'énergie nucléaire du futur", 2021).

21. ASN, "Opinion 2020-AV-0363…", *op. cit.*, p. 5.

This 30-year period is not currently in the law, so it is up to public authorities to make the decision. Depleted uranium is a bona fide energy material resource for the future. Moreover, the volumes involved will remain relatively small, costs will remain limited, and the challenges in terms of safety and environmental impacts will be marginal.

If economic and geopolitical factors made it sensible to re-enrich all the depleted uranium stored in France, then the quantities available would provide fuel to keep the existing fleet operating for about eight years[22]. This time horizon is consistent with what could be achieved by constituting strategic stockpiles of resources at every level of the cycle (again, because of the very high density of the energy content in these materials). By contrast, a fleet of fast reactors with the same capacity as the existing fleet would, with the same quantities of depleted uranium stored in France, be able to function for several centuries and even several millennia (becoming in this case a resource for all of Europe or the world). This gives an idea of the difficulty of predicting today whether these materials will be classified as waste and the benefits of waiting to see what scientific and technological progress will be made over the coming decades.

VLLW and the absence of a release threshold in France

A release threshold is a level of radioactivity below which nuclear waste can be released, meaning it is considered non-radioactive, and is recyclable by industry. French law stipulates that any object, material or waste that was used or produced within an area of a nuclear power plant that "possibly produces nuclear waste" is considered radioactive waste, regardless of its effective level of radioactivity. It therefore cannot be recycled or, if it is machinery, it cannot be reused: it must be stored in a facility designed to hold nuclear waste.

When it comes to VLLW, Andra currently considers that the radioactivity of a large percentage of the waste stored in specialised centres (between 30 and 50%) is infinitesimal or non-existent. The provisions in French law that forbid any possibility of recycling or valorising these materials or this equipment outside the nuclear industry are specific to France. Other European countries with nuclear power plants do not apply this "zoning" principle but instead set a threshold, called the release threshold, below which the object is not considered to pose any danger and can be used like any other ordinary object of the same type. This threshold is currently set at 0.01 mSv, which is 300 times below natural radioactivity and well below the variations in natural radioactivity in certain parts of France, and even variations between living on the 1st or 20th storey of a residential building. This French specificity raises a number of questions:

22. Relying heavily on enrichment capacities (which it will of course be necessary to anticipate).

– Neighbouring countries freely export materials including elements from nuclear power plants with radioactivity levels below the threshold set for Europe. France is able to import these materials, just like any other ordinary ones, without any specific traceability requirements;

– The absence of a release threshold in France rules out any trace of radioactivity for products resulting from dismantlement, even though French regulations allow individuals to receive natural radioactivity or radioactive doses when engaging in certain uses (medicine);

– The absence of a release threshold prevents products with negligible radioactivity levels from being subsequently used.

This is an example of a measure that is unjustified and results in products being discarded without considering their real health impact or how they could possibly be reused (going against the principle of the circular economy). It was enacted at a time when the consequences seemed far off in the future. Now it will have an impact in terms of the costs and construction of storage facilities, which will in turn require materials and generate waste, all to store materials that in reality do not constitute waste and are not dangerous. This assessment is straightforward, and was notably laid out in a 2020 report by the CGE and CGEDD[23], and yet we are still awaiting a decision that is at this stage in the hands of policymakers.

c) Comments on the French government's review of the factors determining efficient management of waste

An analysis of the decisions taken or opinions issued in recent years by the Parliament, safety authorities and scientists from the CNE shows how the lack of clarity and consistency in the government's energy and nuclear strategy makes it difficult to plan ahead and develop the industrial tools that will be necessary 10, 20 or 30 years down the road to manage nuclear waste under the right conditions, even though solutions exist for managing all kinds of waste in terms of fuel cycle equipment, matrices and containers, storage and disposal.

It is also interesting to note that the documents issued by government agencies (notably the Multiyear Energy Plan) and Parliament do not include a prospective analysis looking at the long term for nuclear energy and electricity in a precise and systemic way, or an analysis of the industrial challenges that will be created and the issues that will arise around operational implementation. The industrial, scientific and economics skills

23. Pierre-Frank Chevet, Jean-Philippe Duranton and Philippe Follenfant, "Le démantèlement des installations nucléaires. Enjeux techniques et opérationnels du développement d'une filière industrielle française", CGEDD report No. 012756-01-CGE n° 2019/04/CGE/SG, March 2020 (www.economie.gouv.fr/files/files/directions_services/cge/demantelement-nucleaire.pdf).

that would be required to conduct such analyses are rarely sought by or found within State agencies anymore. The ASN and CNE may require some of this expertise, but those agencies only oversee certain aspects of nuclear waste – safety for ASN and the evaluation of the scientific quality of research into waste for the CNE. Neither agency is responsible for setting the country's nuclear strategy or its waste management strategy. This also explains why their opinions pay relatively little attention to the hierarchisation of issues, including health impacts, and contain few analyses of what the most important issues for the French power system and nuclear industry will be going forward, for instance a roadmap for fast reactors or the potential benefits of multiple recycling in PWRs relative to fast reactor technologies.

In addition to these subjects being addressed by a fragmented State apparatus, expertise has also been lost in the fields of systemic, scientific and industrial prospective analysis. From this standpoint, the 2020 Multiyear Energy Plan gives a good illustration of how, with the successive energy laws adopted in recent years[24], the DGEC and administrative bodies in charge of energy have gradually focused their attention on the progress made toward tens of goals that are often incompatible and not all equally logical, rather than taking an in-depth look at end-goals and industrial implementation conditions[25]. This absence of in-depth prospective analysis and operational breadth in the thinking behind the objectives ultimately undermines their credibility and their robustness over time.

Comments on nuclear strategy in an uncertain world

A nuclear strategy must factor in uncertainties over the medium and long terms (risks/opportunities) by opening up R&D options that lay the groundwork for finding the best possible solutions of the future, while enabling relevant and "no-regret" investment decisions to be taken today. We need to know how to conduct surveys in an open-minded way into subjects that, by nature, lead to discoveries and innovations and thus ensure that our actions reflect the circumstances at all times.

The benefits of open-ended and active research into fast reactors

The reports published regularly by the IAEA* give an idea of possible resources accessible at reasonable cost, i.e. below $260 per kilo of uranium, knowing that prices are currently close to $60/kg, which is fairly low relative to recent decades. These

24. See, in particular, Law No. 2015-992 of 17 August 2015 on the energy transition for green growth (www.legifrance.gouv.fr/loda/id/JORFTEXT000031044385/).

25. See Jean-Paul Bouttes, "Quelle politique de l'énergie pour assurer la compétitivité de notre économie, réduire notre dépendance extérieure et protéger l'environnement"?, talk given to the Academy of Moral and Political Science, canalacademies.com, 3 July 2017 (www.canalacademies.com/emissions/en-seance-avec-debat/quelle-politique-de-lenergie-pour-assurer-la-competitivite-de-notre-economie-reduire-notre-dependance-exterieure-et-proteger-lenvironnement), *in* Michel Pébereau (dir), *Réformes et Transformations*, PUF, 2018, p. 235-280).

resources would represent about 15 million tonnes, enough to keep global installed nuclear power capacity 2.5 times greater than the existing fleet operating for 100 years.

That said, one cannot rule out pleasant surprises that would push back far into the future the need for a massive deployment of fast reactors. We could for instance, over the coming decades, discover several new giant deposits with sufficient natural uranium content, like the Olympic Dam in Australia, or the research underway into uranium extraction from seawater could lead to a credible industrial development plan**. This would allow electricity to be produced massively, on a global scale and for several centuries, solely with light water reactors (primarily using uranium 235).

If a large-scale deployment of fast reactors only makes sense once they can compete with water-cooled reactors, then it seems overly optimistic to take the long-term abundance of uranium for granted. Continuing a credible research programme into fast reactors should, within the next few decades, give us access to a technology that is safe and industrially robust, one we can be ready to deploy if uranium becomes economically scarce (and due to geopolitical energy constraints)***. Indeed, we know that by 2050-2100 sodium reactors may be at industrial scale, either small models (SMRs) or large ones with cores similar to Astrid (though it will entail additional investment costs, which must be kept in check). Implementing such a research programme leaves time to explore the full range of technical possibilities for sodium reactors but also to study the potential of other fast reactor technologies such as molten salt. It also allows us to be demanding when it comes to the robustness and simplicity of designs, which could potentially be key to bringing investment costs into line with those of water-cooled reactors. Moreover, this is an option that could help optimise waste management (supplementing disposal).

While some countries may, as is the case today, opt for water-cooled reactors and an open fuel cycle with geological disposal of spent fuel, given the uncertainty that lies ahead, it seems safer to work on mastering fast technologies through international cooperation, knowing that the reactors would only be deployed once it made economic sense to do so.

Charting a clear and sustainable course for R&D strategy and ensuring that the conditions for industrial and economic success are in place in the event of massive deployments

The decisions that need to be taken can be divided into three categories, with potentially significant financial impacts and covering different timescales:

– The resources required for early research in laboratories, representing tens or hundreds of millions of euros;

* See IAEA-NEA, *Uranium 2020. Resources, Production and Demand*, 2020, p. 15 (www.oecd-nea.org/jcms/pl_52718/uranium-2020-resources-production-and-demand?details=true). Prior editions can be found at www.oecd-nea.org.

** On this topic, also see recent research in China on performance membranes:

Xiao Xu *et al.*, "Ultrahigh and economical uranium extraction from seawater via interconnected open-pore architecture poly(amidoxime) fiber", *Journal of Materials Chemistry*, vol. 8, No. 42, September 2020.

*** Mastering this technology at industrial scale would also allow France to guarantee its energy independence over the very long term by making use of its stockpiles of nuclear materials.

– The move to the pre-industrial phase via full-scale demonstrators, which will cost hundreds of millions or billions of euros;

– Investments related to the massive deployment of power plants (with the related fuel cycle equipment), representing tens or hundreds of billions of euros.

A technology can only be rolled out on a massive scale once it is economically competitive, including to ensure the country's economic sovereignty. A shift to the industrial demonstrator phase requires clear prioritisation based on industrial maturity (timeframe for becoming competitive and feasible at scale) and utility (service provided). Early research must be conceived in broad terms, taking into account the full range of possibilities over the long term and relying on international cooperation.

A commitment to the Cigeo project, an extension of the operating lifetime of existing reactors, or a commitment to begin building a series of EPRs, fall into the category of decisions to be taken for a massive deployment that would be relevant today; light water SMRs (NUWARD)**** will soon be ready for a large-scale demonstrator, and we must position ourselves to allow fast sodium reactors to reach that phase as well by 2040 or 2050; lastly, when it comes to early research, there should be a roadmap that is open to other technologies, with perhaps a special focus on molten salt (which could also open the door to using thorium). European and international cooperation is important, but it will be even more useful if we have invested in certain areas ahead of time to build lasting industrial and scientific skills.

**** Small Modular Reactors (SMRs) are nuclear reactors with small unit size and capacity of less than or equal to 300 MW, that are manufactured, wherever possible, in factories in a standardised way.

2. Making the Cigeo project a success: Efficient industrial management and operational governance

The Cigeo site is undoubtedly one of the best geologies in France for disposing of HLW and ILW-LL, provided that industrial implementation of the project is successful in terms of safety and costs. This is a major, complex industrial project, a unique "first-in-series" structure the construction and operation of which should span more than a century. If it is approved by public authorities, we must consider the scope of the next steps to be taken, predominantly operational and industrial. It will be important during this next phase to guarantee the effectiveness of the industrial choices over time by ensuring that responsibilities and the operational governance structure are clear and understandable to all. Policymakers must decide quickly whether to move forward with Cigeo and, if they approve the project, they must set about putting the proper operational governance into place.

a) Industrial management of a large and complex project over 100 years

Lessons that can be drawn from the recent past in terms of industrial choices

The evolution of cost estimates over the past two decades, during which we gradually moved from applied research to industrial scale, underscores the importance of laying out clear end-goals and specifications for projects ahead of time and considering operational decisions based on studies that look at safety, industrial feasibility and costs. Experience has shown that, for large projects developed in a context of strict regulations, the more effort is made to avoid useless complexities and contradictory orders in specifications, the greater the chances of achieving industrial feasibility, safety and cost control. Cost estimates shot up from 10-15 billion euros in 2000-2005 to 35 billion euros in the early 2010s, before falling back down to 25 billion euros in 2016 thanks to work done by Andra engineers with waste producers EDF, CEA and Orano. This corresponds to the non-discounted sum of investment costs and facility operating expenses over 100 years for the disposal of HLW and ILW-LL from existing nuclear power plants over their operating lifespan (50 to 60 years), as well as legacy waste of the same type from other nuclear activities (research, industry, medical, defence).

Examples of areas in which choices had to be made that affected the complexity of the design and costs, and which illustrate the importance of operational management that takes into account safety, industrial feasibility as well as costs, include:

– The key role of surface facilities, notably due to the options selected in terms of package handling and verification;

– The decision regarding the waste transfer ramp system in addition to shafts to link deep disposal areas to the surface: the goal here is to limit the consequences of packages falling, illustrating the trade-offs necessary between coherent choices for surface-depth connections, handling options and container design to ensure a same level of safety. The approach will differ for different types of ILW-LL and HLW. It is also important to not have too many surface-subsoil connections to avoid impacting the confinement qualities of the rock;

– The design and support structures for the deep tunnels and cells, which will be determined in large part by package recoverability requirements: given how slowly tectonic plates evolve, seeking to ensure recoverability beyond 100 years implies creating cells and tunnels that follow a given axis in a straight line, which is what determines the drilling systems and the use of more sophisticated tunnel boring machines;

– The choice of a 40-year time gap between the storage of ILW-LL, which could start upon completion of the "pilot phase" (first 10-15 years of construction and tests), and the storage of HLW that needs to cool for at least 60 years before being disposed of: this time gap adds to construction time, and thus to complexity and requirements in terms of skills maintenance over time, and drives up costs (a decision could have been made to "synchronise" the storage of the two types of waste, bearing in mind that other factors justify starting with ILW-LL storage, without waiting for HLW disposal to be ready).

The lessons to be drawn from recent years will be particularly relevant as we move toward the industrial phase, during which similar problems will need to be analysed and addressed in an efficient and coherent way over several decades.

Industrial management requirements if the project moves forward

The target cost for Cigeo was set by ministerial decree in January 2016, for the 2016-2156 period, at 25 billion euros. Half of these costs are for investments. Optimisations were proposed and approved as part of the work undertaken with producers' engineers: technical opportunities, reduced purchasing costs, productivity gains, greater industrial efficiency, and longer-term gains.

The decree also specifies that this cost "is to be updated regularly and at least at each key development phase of the project (authorisation to build, commissioning, end of "industrial pilot phase", safety reviews), in accordance with the opinion issued by the Nuclear Safety Authority[26]".

The quality of the options selected in terms of design (simplicity, robustness vis-à-vis project objectives), as well as the quality of industrial management, are the keys to being able to provide the anticipated protections to distant future generations, which ties in with the ability to meet budgets and deadlines.

Several industrial options remain on the table today, notably:

– Methods for storing bituminous waste: waste producers and Andra are conducting additional studies on ways to either neutralise the bitumen products prior to storage or to adapt storage systems. These methods will be submitted to the ASN for approval;

– Methods for verifying packages before and after burial: systematic controls by producers and Andra prior to their arrival at the site and either systematic or random once they are at the site, to be determined;

26. Decree of 15 January 2016 related to the cost associated with the implementation of long-term solutions for managing high-level and intermediate-level waste-long lived, art. 2 (www.legifrance.gouv.fr/loda/id/JORFTEXT000031845115/).

– Design of storage zones for HLW: optimisation of the length of cells, of the centre distance, of cell design;

– Methods for closing cells: on this topic, we could mention the process of producing hydrogen from corrosion of the steel (steel reinforcement of cells, lining…) present primarily in HLW sections where reversibility requirements lead to its use in large quantities[27]. This hydrogen production, the exclusive result of long-term recoverability requirements, is yet another example of the potentially negative impact, in terms not just of costs but also of additional complexity and potential risks for the safety of workers over the coming decades, of not closing cells once they have been filled;

– Multiple provisions related to reversibility/recoverability requirements;

– Scheduling for starting work on transport (roads, railroads…).

While these options require very high-level engineering expertise (expertise that Andra is already in the processing of securing), past experience suggests that all studies should also include quality risk and cost/benefit analyses to help guide choices.

These studies, focusing simultaneously on all three aspects – industrial, safety and costs – are indispensable for the operational manager of the project, Andra, and to allow for a quality consultation with stakeholders, especially local authorities and residents in the areas in question. They are also indispensable to the decision-making process of the DGEC and, beyond that agency, of the government's administration and Parliament. This assumes that the right multidisciplinary and transversal expertise exists and is leveraged by the State to promote the general interest. It also assumes that responsibilities will be assigned in a clear way and that governance of the project, if it does move forward, will fully reflect the central role to be played by industrial management.

b) A governance structure that is complex, inherited from the past, and will need to be adapted for the industrial implementation phase

A major project with multiple challenges and multiple actors involved

This complexity relates to the characteristics of this major project, designed to last for a century and to tackle a number of different challenges simultaneously:

– An industrial project meant to protect future generations from the dangers of HLW and ILW-LL;

27. See CNE (2021), *op. cit.*, p. 41.

– A nuclear project that raises safety and security issues for workers at the site and for local communities today, and safety issues over the long term;

– A project that brings together different areas of applied research (geology, geotechnology, chemistry, materials, numerical modelling…), and raises questions about the orientation and financing of that research;

– A project that has major consequences at the local level and raises questions about taxation and its effective use for local development;

– A project that, beyond its specific end-goal, crystallises national debates about nuclear and energy strategy, and tests the level of confidence people have in technology and science as well as in the State and politicians;

– A project the scope of which, in terms of the inventory of waste to be stored, will naturally depend on the country's energy and nuclear policies (reference inventory and reserve inventory);

– A project that is funded by waste producers, which are legally responsible for the waste and operationally responsible for its packaging, transport and interim storage. The two temporalities – that of Cigeo and that of these operations, particularly temporary storage – must necessarily be coherent.

Because it brings all these issues and challenges together, the project is characterised by a large number of actors involved via a multitude of agencies: OPECST, DGEC, ASN, IRSN, CNE, HCTSIN, PNGMDR… In this next phase, during which some challenges will be new and operational, it will be important to have clear responses to simple questions:

– Who is responsible for what, and who decides what?

– Who issues opinions on a given subject, and on the basis of what competencies?

– Who ensures that the overall vision is being followed and takes responsibility for the subject as a whole as well as the concrete consequences of decisions taken, and this at all different levels of logic (from politicians up to operators)?

The importance of having operational governance that is simple and understandable if the project is launched

Systemic responsibility appears that much more important considering the questions below, which will need to be addressed in future:

– How will the nuclear strategy evolve and what impact will it have on stockpile of waste that requires geological disposal?

– When will the filled cells need to be closed?

– Who is responsible and accountable for ensuring coherency between the timetables for extending or renewing temporary storage facilities and the timescales for disposing of different categories of waste at Cigeo?

– Unlike Sweden and Finland, where subsidiaries of waste producers are jointly responsible for the safety, financing and industrial implementation of geological disposal, and contrary to the United States, where the federal government, via an arm of the US Department of Energy (DOE) is responsible for all three roles (waste producers add a tax to customers' electric bills which goes to the federal government), in France, producers are legally and financially liable, but it is Andra, under the aegis of the government via the DGEC, that is tasked with ensuring the safety and industrial implementation of the project.

Here again, how can governance serve to ensure the existence of a leader that truly guarantees responsibility and accountability for and oversight of every aspect of the subject?

With the regulatory steps being taken and a launch decision potentially on the horizon, Cigeo is entering a new industrial phase, with specific conditions that must be met for it to be a success, chief among them the quality of governance that flows from that operational dimension. In the words of the CNE: "The Commission underscores the importance of having a clear and shared definition of the scope of operational governance for Cigeo and how it should be implemented, starting when the creation of the disposal facility is authorised. Any plan adopted must define who is involved, why, how and when. Simplicity is key to efficiency in this case[28]".

Feedback from large-scale industrial projects shows that implementation is successful when projects are as simple as possible, when governance and decision-making chains are understandable and designed to meet clear objectives: protect distant future generations but also guarantee the safety of workers and communities while the facilities are in operation and optimise costs for present generations.

c) Clarify the process for committing to Cigeo and make a decision to move forward by creating the conditions for its success

Decisions about committing to the project should be clarified on a timeframe consistent with regulatory deadlines, yet no clear management decision has been taken regarding Cigeo as of today. Though it may remain controversial, the project is the result of a lengthy legislative process that opened the debate, and of a lengthy consultation process with all stakeholders weighing in about

28. *Ibid.*, p. 45.

the choice of this disposal option, which is recommended internationally. In the words of Bernard Doroszczuk, president of the ASN: "The next plan, spanning a period of five years, will need to clearly be about solutions that will allow us, over the next 20 years, to provide adequate storage capacity for the waste generated by dismantlement operations, the management and packaging of older waste, and the continued operation of existing reactors. As we know, time horizons are long in the nuclear industry. Once a project has been approved, it takes about 15 years for it to become operational. This means that decisions must be taken by 2025 about solutions that will allow us to meet storage needs for all types of waste in France in 2040[29]".

Based on the analyses above, committing to Cigeo appears to be a satisfactory long-term solution that will benefit from Andra's increasing expertise in industrial aspects. It is thus time for public authorities to make a clear decision. And it will be important for governance to be reshaped quickly after that to effectively protect present and future generations by ensuring that the project advances on time and on budget.

VI. DEBATES IN FRANCE ABOUT HIGH-LEVEL NUCLEAR WASTE: LOOKING AT HISTORY AND LESSONS TO IMPROVE DEMOCRACY

The history of debates about nuclear waste in recent decades in France gives a good illustration of the difficulties that must be overcome to better understand all health, scientific and industrial issues and to design and implement the right solutions. Nuclear waste management is scientifically and technically complex, and it requires ensuring the involvement and cooperation of experts from different disciplines with different skills, through an always open-ended process of surveys and knowledge accumulation. The subject affects not only future generations, but also the interests of many stakeholders that are part of current generations, starting with communities and elected officials near industrial waste management sites, as well as those working in science and industry. Moreover, the semantic field of the terms "waste" and "nuclear" tie in with other questions, from the energy and nuclear policy of the country in question to positions on the role of the State and its technostructure, or trust in science and progress.

It is necessary to design democratic institutions that can differentiate between different logical levels (transversal scientific expertise, consultations with

29. Bernard Doroszczuk, "Presentation of the 2020 annual report of the Nuclear Safety Authority (ASN)", Senate, OPECST minutes, session of Thursday 27 May 2021.

stakeholders, political and societal issues) to enable kinds of cooperation that are adapted to each level, while also ensuring that they jointly promote the active participation of citizens and effective policy decisions that reflect the evolution of these systemic problems and circumstances.

1. Retrospective[30]

a) 1950-1975

Nuclear was initially developed in the 1945-1960 period, for military purposes. The defence industry was the first, along with the medical sector, to face the need for waste management. During these years when the technology was just emerging, the handling of defence-related waste was shrouded in secrecy, as only partial information was available about the potential health consequences of this new technology (knowing that, in the United States, the scientists developing military projects in the 1945-1950s were very focused on protecting workers). Some waste was not managed with enough precaution or skill, and a few sites (primarily in the USSR) became examples of what not to do, sending a warning about the dangers posed by this waste and the need for careful management and scientific and technical research to prevent risks (a notable example is the Kyshtym industrial site in the Techa river valley, in the USSR, where radioactive effluents were managed with no precautions and a disaster occurred in 1957 but was kept secret until the 1980s). In the mid-1950s, the significant presence of radiobiologists and the desire of countries like the United States (and United Kingdom) to develop civil nuclear power (Atoms for Peace conference of 1954[31]), led the scientific community to quickly explore potential solutions that involved dilution in the ocean versus confinement in surface storage facilities, then geological disposal under the continents or in stable sediment layers of the ocean floor. Starting in 1957, the US National Academy of Science began recommending deep geological disposal.

In the 1960-1970s, research began to expand to include scientific communities from a variety of disciplines: nuclear physics and neutronics, radiobiology, chemistry, geology, oceanography, materials…

30. For this section, see in particular: Yannick Barthe, *Le Pouvoir d'indécision. La mise en politique des déchets nucléaires*, Economica, 2006; Aude Le Dars, *Pour une gestion durable des déchets nucléaires*, PUF, 2004; Jean Claude Petit, "Le stockage des déchets radioactifs : perspective historique et analyse sociotechnique", doctoral thesis, Paris, Sociology of Innovation Centre, École nationale supérieure des mines, 1993; Julie Blanck, "Gouverner par le temps : la gestion des déchets radioactifs en France, entre changements organisationnels et construction de solutions techniques irréversibles (1950-2014)", thesis for doctorate in sociology, Paris, Institut d'études politiques, 2017; Michèle Chouchan (ed.), *Faut-il avoir peur des déchets radioactifs ?*, Andra, 2003.

31. "Atoms for Peace" refers to the programme designed by the United States to promote the use of nuclear technology for peaceful purposes.

International agencies would play an important role in organising this interdisciplinary research: the IAEA and NEA were created in 1957, the first scientific congresses were held in the late 1950s and, in the 1960s, the Commission of the European Communities (CEC) became involved. They notably highlighted the need to study the consequences of introducing radioactive elements into the food chain via the possible contamination of living organisms in oceans if waste is immersed, and the risk of reconcentration until it reaches humans. Studies of different potential sites in salt mines raised questions about the long-term permeability of some of them. Hence the interest in studying confinement materials (matrices, packages, containers, engineered barriers) that could compensate for the weaknesses of some geologies and slow the radionuclide dispersion process. This research into matrices and packages-containers also held potentially great promise for making temporary surface storage secure.

In the 1970s, France was rolling out civil nuclear power at an industrial scale, per the Messmer plan introduced in 1974 in response to the oil shocks, just as concerns were beginning to be expressed about environmental and health issues. These concerns came first and foremost from the scientists working on nuclear technology and particle physics. For instance, a manifesto signed by 400 scientists in February 1975 warned about uncertainties, notably as regards the ability to extrapolate to a scale of several millennia experiments done to test the resistance of materials to external aggressions such as water. The scientific and technical technostructures in charge of addressing these issues, such as the CEA, the BRGM and EDF, stepped up their research programmes and efforts to move to industrial scale: ocean immersion was abandoned, nuclear physicists from the CEA began working on transmutation (starting with that of plutonium with fast neutron reactors), geologists from the BRGM and CEA went to work on geological disposal through large-scale international programmes (CEC, OECD), France and the United Kingdom were focusing especially on granite while other countries were looking at salt or clay, and the CEA began developing in the early 1970s a prototype plant, in Marcoule, for vitrification.

Debates on all these topics were intense since these were new areas presenting many uncertainties that research needed to identify, clarify and, if possible, allay. The different regions were not very affected since the only industrial-scale developments at the time were nuclear power plants; other aspects were still in the research or prototype phase. The primary sources of controversies were thus the scientists and engineers working on these issues, along with CFDT union activists from the CEA and EDF, academics and CNRS researchers working in the field of nuclear physics and energy economics, who mostly stressed the still numerous scientific and technical questions that remained unanswered at that stage and the tendency of technostructures to underestimate them.

Nuclear thus became a cutting-edge sector for innovation in the area of waste management solutions over all time horizons, but within a context where the debate was between researchers from different disciplines and where the State decided on the direction research should take based on input from the major public scientific and technological organisations, with no structured consultation with the regions and citizens, while at the same time starting to listen to the plurality of voices within the scientific community.

b) 1976-1990

Between 1975 and 1985, strong opposition to nuclear waste would emerge, in areas going beyond the issues of science, technology and health associated with the safe and efficient management of waste. French ecologists made nuclear the symbol of their fight for the environment and their reservations about progress, science and technology, focusing both on the civil and military nuclear programmes carried out by the scientific and technological technostructure (CEA, EDF, BRGM…) left over from the "30 Glorious Years", rather than setting their sights on oil, automobiles, and consumers. This choice may have stemmed from a legacy of pacifism marked by opposition to atomic weapons, considered the symbol of Promethean man. It undoubtedly also made it easier to tie in with criticisms of technocratic state capitalism, but, helpfully, without directly calling into question how the French went about their daily lives or the main private economic forces. Some in the socialist left also became anti-nuclear as part of their fight against the centralised State and/or against the industrial capitalist society that promotes mass consumption. Alain Touraine, with other sociologists, published a book called *Anti-Nuclear Protest*[32]. A review in French newspaper *Le Monde* said the book could be summarised as follows: "Social conflicts aren't what they used to be: instead of pitting workers against bosses, they now see communities opposing apparatuses seeking to impose on them a model for conduct and a collective future[33]". The review went on include a few quotes from Alain Touraine himself: "It is not the plutonium that brings in technocracy, but rather the technocratic power that imposes an all-nuclear policy […]. They [anti-nuclear activists] create models of knowledge, of economic activity and of moral conduct that are post-industrial". The author's approach is made clear in the opening pages of his book: "If we try to find among today's social struggles the social movement and conflict that will take over the central role played by

32. Alain Touraine, Zsuzsa Hegedus, François Dubet and Michel Wieviorka, *La Prophétie anti-nucléaire*, Seuil, 1980.

33. Marc Ambroise-Rendu, "La Prophétie anti-nucléaire", by Alain Touraine, *Le Monde*, 15 March 1980 (subscribers only: www.lemonde.fr/archives/article/1980/03/15/la-prophetie-anti-nucleaire-d-alain-touraine_2815990_1819218.html).

the working-class movement and labour conflicts in industrial society, we see the anti-nuclear movement as the most infused with social movement and protest, and the most likely to produce a counter-model of society[34]".

Within the scientific world, plans for research into and industrial implementation of different waste management solutions also gave rise to competition for funding between oceanographers, geologists, and experts in nuclear physics and transmutation. It was within this context of emulation between different scientific disciplines and organisations that the scientists critical of nuclear were stressing the uncertainty that remained around long-term solutions and the protection of future generations. Their objections, often accurate and just, focused on the need to leave time for research to explore certain issues in more depth. Yet, during political debates, these relevant criticisms got turned into cartoonish and adamant slogans, making it seems like there was no solution for managing long-lived nuclear waste and that this waste was therefore the great weakness of nuclear power.

Instead of carrying out the necessary investigations and keeping multiple options open, those in charge of nuclear policy believed they could understand and satisfy the expectations of civil society by accelerating decision-making and working to implement as quickly as possible the solution they believed was the best one, geological disposal; as discussed in volume 2, research done over the past three decades has confirmed the advantages of this solution. However, in 1980, uncertainty remained. Some leaders believed that the only way forward was to find a perfect solution, one with no drawbacks at all, and implement it immediately (this approach was questionable to say the least, especially for scientists). As a result, plans for deep disposal in subsea sediment were abandoned, as was research into transmutation, as the focus shifted to seeking out the best possible sites for disposal in a technocratic manner, without really taking into account the concerns and expectations of local authorities and actors. The Castaing Commission, which worked for the government and submitted three reports on waste and related topics between 1981 and 1985, sought to correct these shortcomings by bringing together scientists from different backgrounds and adding critical scientific and technological voices, while at the same time encouraging efforts in the three key areas identified later in the Bataille law. In practice, however, the top priority became quickly finding geological disposal sites with the right technical properties when it comes to confinement safety, without any real prior consultation with local actors.

This strategy led to a political impasse in the late 1980s, with strong local opposition to the four sites selected once geologists from Andra (which was an integral part of the CEA at the time) attempted to start their work at

34. Alain Touraine, Zsuzsa Hegedus, François Dubet and Michel Wieviorka, *op. cit.*, p. 11.

those sites. Anti-nuclear activities echoed the concerns of local opponents at the national level, helping to cement the public's negative view of nuclear, during a decade that saw the Chernobyl disaster in the USSR (1986). This situation of militant opposition in the public sphere between scientists who were "critical" and scientists who were "in charge" led, on both sides, to demands for an ironclad solution that would hold for millions of years and be available immediately, an attitude that, paradoxically, is more Promethean than representative of the spirit of scientific inquiry and our capacity to make reasoned and measured decisions.

c) 1991-2006

With the country at an impasse, then-prime minister Michel Rocard put politics and the Parliament back at the heart of the debate by asking the OPECST and a National Assembly member from the Nord department, Christian Bataille, to assess the situation and submit a series of proposals that would become the "Bataille Law" of 30 December 1991. As we saw in volume 2, this process put options back on the table by initiating 15 years of applied R&D around three areas: partitioning and transmutation, long-term storage and geological disposal with different types of geologies studied (clay, granite…) and several sites considered for laboratories rather than the immediate development of a final nuclear waste disposal facility. The CNE was created, bringing together independent scientists from different disciplines responsible for assessing the quality of the research done and proposing orientations to guide the OPECST and public authorities. Political factors took precedence over technical ones when it came to searching for sites for disposal laboratories: the first step was to talk to the regions that might be involved, then to listen to local actors, elected officials, associations and residents, to hear their concerns and confirm their willingness. Only then were "candidate sites" shortlisted based on technical and scientific criteria relating to the quality of their geologies.

This process led to the selection of four new potential sites: clay in the Meuse, Haute-Marne and Gard departments, and granite in the Vienne.

Local Information and Monitoring Committees (comités locaux d'information et de suivi – CLIS) were set up at each site where a laboratory was to be built, with local elected officials and relevant associations involved, similar to what was done with the Local Information Commissions (CLIs) created around nuclear power plants.

The functioning of the OPECST offers a good illustration of the spirit of these institutional innovations. The goal is to look beyond the official expertise of the large organisations that are part of the State apparatus to also bring in other scientific and technical opinions as well as the viewpoints of local elected officials and citizens and the interests defended by activist associations. This effort to hear the plurality of arguments went hand in hand with a focus on drawing a distinction between the different levels of logic of the arguments: scientific and technological discourse on the dangers of and solutions for waste, the country's energy and nuclear policy, the role of the State and the functioning of democracy, critiques of industrial society, interests associated with local development and concerns about the image of regions due to the symbolism and imagery associated with nuclear waste and its burial (conjuring up images of atomic weapons, the underground where dead bodies are buried or fears of hellish worlds), and values and ethical reasoning when it comes to future generations. In conducting hearings, the goal was to show openness to all these concerns and incorporate them into a political framework that was clearly a neutral arbiter. Christian Bataille was obviously chosen as rapporteur because he was an elected official with no preconceived opinions on the subject, from a region not affected by potential solutions given its geology. And yet the objective was also, clearly, to identify a process for ultimately finding concrete waste management solutions that would keep distant future generations safe.

During this period, which saw the oil and gas counter-shock, the competitiveness of nuclear relative to combined-cycle gas turbine plants was jeopardised. Moreover, the deregulation of public service networks such as the electricity and gas grids (with competition introduced in these areas) also undermined large public entities like EDF and the CEA. Taken together, these developments made a reopening of debates seem timely[35]. Given the energy and institutional context (little mind was paid to climate issues at the time), it made sense for some of those responsible for energy policy for the State and at EDF to start asking questions about the economic benefits of reprocessing (relative to an open fuel cycle) or building new nuclear power plants (rather than combined-cycle gas turbine plants). Within these debates, regardless of political positions, two key ideas seemed to be shared by most: first, progress made in recent decades would quickly yield satisfactory technological solutions for managing nuclear waste; and second, even if no new nuclear power plants were built and reprocessing ceased, the nuclear waste that already existed or would be produced still needed to be managed, and the responsible thing to do was to implement adapted solutions. The debate about waste management solutions thus became less weaponised than the one about the future of civil nuclear power.

35. See, for example, the report by Jean-Michel Charpin, Benjamin Dessus and René Pellat, "Étude économique prospective de la filière électrique nucléaire", report submitted to the Prime Minister, July 2000 (www.vie-publique.fr/sites/default/files/rapport/pdf/004001472.pdf) and the related debates.

This (largely bipartisan) process, inspired in part by the approaches taken in Sweden and Finland, led to considerable advances in terms of research and the involvement of actors. It resulted in the passage of the law of 2006, following a national public debate organised by France's National Public Debate Commission (Commission nationale du débat public – CNDP) and based on a series of documents produced by the OPECST, the CNE, the ASN, the CEA and Andra, all remarkable documents in terms of quality of analysis. The law of 2006 stressed the complementarity of the three areas of research, acknowledging that the outlook for transmutation was more distant and less certain (beyond plutonium with fast reactors), identifying the Meuse/Haute-Marne site as the benchmark solution for geological disposal, and preserving storage as a useful but non-permanent complementary solution. The law paved the way for the Cigeo project for disposal and the Astrid project for fast neutrons. This approach, driven by participatory democracy organised and conducted through national representation in Parliament, yielded concrete and positive results on three key levels: first, in terms of allowing research to help frame uncertainties and provide partial answers to many of the questions raised; second, by allowing the relevant stakeholders and communities to participate; and third, in terms of policy decisions.

We can nonetheless identify two weaknesses in this approach. While the humanities, and notably sociology, were clearly given a role in the process[36], there was little discussion of why a permanent disposal solution was given preference right away over long-term storage, or why the reversibility of geological disposal became an issue with little discussion beyond general references to the expectations of future generations and our responsibilities. It is virtually impossible to find structured reflection on said expectations of future generations as they relate to the health consequences of these long-term decisions, the possible worlds future societies will live in and their capacity to respond, or an analytical framework for studying the risks these developments imply. Nor are ethical philosophies called upon in the spirit of conducting a "collective and well-reasoned inquiry" into the issue of nuclear waste and our responsibilities.

This weakness can be overcome insofar as the elements related to the critical themes that must be identified and studied together already exist, as we saw in volume 3.

The other weakness we could point out is the failure to build another geological disposal laboratory besides the one in the Meuse/Haute- Marne.

36. In addition to the sociology and history texts cited above, see Michel Callon, Pierre Lascoumes and Yannick Barthe, *Agir dans un monde incertain. Essai sur la démocratie technique*, Seuil, 2001; Philippe d'Iribarne, "Les Français et les déchets nucléaires", report submitted to the minister delegate for industry, April 2005 (www.vie-publique.fr/sites/default/files/rapport/pdf/054000355.pdf).

The government's decision in 1998 to scrap plans for the two sites initially shortlisted, clay in the Gard and granite in the Vienne, and to halt the search for alternative sites, was the result of several factors, including concerns within the winegrowing community in the Gard about the impact on the region's brand image and, in both cases, considerations having to do with local politics. On a broader scale, the decision reflected how difficult it is to mobilise scientific expertise in a truly multidisciplinary way to address the issue of risks faced by future generations: how can we prevent radionuclides from being released from these geologies on a distant time horizon? Finding the right solutions requires thinking about sources of complementarity between the characteristics of the geology and engineered barriers, and those of the matrices, packages and containers. This painstaking work was not really performed for the two geologies that were scrapped (contrary to the Cigeo project). The multidisciplinary scientific and technical inquiry required to identify a concrete solution and study its possible health consequences could be further advanced by improving the institutions through which cooperation and interdisciplinary work are organised.

d) 2007-2020

The law of 2006 has guided developments in recent years: continued research in the different target areas, preparation for the industrial implementation of Cigeo (finalisation of design, build-up of engineering and execution skills within Andra), and the rollout of successive versions of the PNGMDR on the traceability of waste and planning of related management tools.

The public debates organised by the National Public Debates Commission (CNDP) around the PNGMDRs and progress on the Cigeo project revealed the growing radicalisation of a handful of anti-nuclear activists who manipulated these debates, sometimes using violence to prevent them from taking place. As a result, the scientific and technological progress made in recent decades has only been partially taken into consideration, scientific uncertainties are poorly hierarchised and presented, and the participation of regular citizens has been impeded. This derailing of debates makes it difficult for most actors with real expertise to address issues specifically related to nuclear waste in a rigorous and pedagogical way, particularly to answer citizens' questions about real health risks and oversight of the implementation of management solutions.

Such approaches based on participatory democracy have always made it possible to clear up some controversial scientific and technological points[37] and allow citizens and stakeholders to express their viewpoints in a structured way, but now we must ask ourselves what changes could be made to reenergise them. While summaries of the plurality of viewpoints expressed are always useful[38], it is also necessary to wade through hundreds of pages and countless videos (mostly made with the participation of the same small handful of people), illustrating how difficult it is for regular citizens with concerns to have their voices heard and participate in a real dialogue. This is a sign of the bureaucratisation and hijacking of processes that were so promising initially.

Moreover, as we saw previously, the gradual weakening of France's nuclear strategy over the past decade has made it more difficult to anticipate what actions need to be taken in terms of developing waste management tools and finding the scientific and industrial skills required. The fragmentation of State policy on energy and nuclear issues, and the erosion of the industrial and scientific expertise available to the State in these areas, are the result of a gradual retreat that began in the mid-1990s. We thus found ourselves in a paradoxical situation where debates were effectively opened to all citizens and stakeholders relative to 1960-1990, and much progress was made on the science and technology fronts, but we no longer had any public officials clearly tasked with managing these issues and preparing dossiers to educate citizens and politicians about the future, people with the skills to oversee a safe and efficient implementation.

2. A few lessons to improve democratic institutions

a) Nuclear waste: A complex problem with many facets, representative of "disputed universes"

This brief retrospective illustrates the many facets of the debates raised by the semantic field of nuclear waste in our society. In the words of François Jacq, board chairman of the CEA: "Few topics have generated as much literature in the fields of science, technology, sociology and politics as radioactive waste [...]. Any mention of radioactive waste immediately conjures up a series of images, of symbols, of associations, that come to mind naturally as if sprung from a pre-made imagination. Ideas about the dangers and threats waste poses to societies will always be there in the background – ideas that are ill-defined but always ready to contaminate our world and become vectors of threats that seem even more frightening because they are only vaguely defined. At another level, radioactive waste

37. See Public Debate – National Plan for the Management of Radioactive Materials and Waste, "Clarification of technology controversies. Synopsis", CNDP, 23 March 2019 (https://pngmdr.debatpublic.fr/images/contenu/page-clarification-controverses/PNGMDR_Clarification_controverses_VF.pdf).

38. *Ibid.*

incarnates a form of guilty conscience of contemporary society. It is the hallmark of a society focused on consumption, willing to exploit resources without worrying about the negative impacts that will be part of the legacy created. And in some minds radioactive waste is the ultimate consequence of the scientific and technological "hubris" of humans who have been playing God […], waste is the outgrowth of an economic, political and industrial machine incapable of looking ahead or considering issues that will arise over the medium term[39]".

Given that nuclear is associated with so many mental images, we run the risk of failing to talk about the concrete problems posed by nuclear waste and how it can be managed in a way that protects us from it. It is nonetheless important to acknowledge all these concerns, from the analysis of health risks and specific technological solutions, and the necessary reflection on ethical issues related to future generations, through to questions about science, progress, and the role of the State. We must clarify the issues that need to be worked on and debated in each area, notably so we can build the institutions for dialogue and debate that can produce the necessary collective inquiry, to loosely quote John Dewey[40].

This brings us unequivocally into what some authors call "disputed universes": scientific and technological fields which, due to their complexity, uncertainties, their potential impacts on society and their symbolic power, give rise to controversies that are not just scientific and technological but also societal[41]. In this case it is necessary to broaden the scope of inquiry (once again, loosely quoting John Dewey) to include all these aspects, while making available the resources needed to advance in each area by addressing opposing arguments in a demanding and rigorous way.

During such debates, it is necessary to clarify and draw a distinction between:

– What relates specifically to nuclear waste (what qualifies as waste, what are its potential dangers and management solutions) and the protection of future generations;

– What relates to the various specific interests of present generations: local communities and regions near waste management sites, industrial waste producers, scientists from the different disciplines and organisations involved in research programmes;

39. François Jacq, "Les déchets radioactifs : une histoire, un enjeu", *in* Michèle Chouchan (ed.), *Faut-il avoir peur des déchets radioactifs ?*, Andra, 2003, p. 11-12.

40. See John Dewey, *The Quest for Certainty. A Study of the Relation of Knowledge and Action* [1929], Gallimard, 2014. Also see, for an introduction to the philosophy of John Dewey, Stéphane Madelrieux, *La Philosophie de John Dewey*, Vrin, 2016.

41. See Olivier Godard, *Environnement et développement durable. Une approche méta-économique*, De Boeck, 2015, p. 90.

– What relates to debates for present generations, opposing different schools of thought, on related societal themes such as the role of the State, science and progress, and energy policy;

– Lastly, what relates to our ability to implement the solutions chosen, both operationally and industrially, and to debate the best industrial governance.

b) Significant advances in "technological democracy" over the past decades but some weaknesses still need to be corrected

The scientific and technological progress made in recent decades is impressive. Advances have helped map out the field of possibilities and significantly reduce uncertainty for decision-makers, while also paving the way for innovation going forward. The "incremental" political process adopted in 1991 and the institutions created for scientific and technological discussion and debate (OPECST, CNE, CNDP…) also form a solid foundation for the future. Additionally, they have proved efficacious in concrete ways when it comes to the effective management of waste via the PNGMDR or the development of the Cigeo disposal project.

Indeed, the thousands of pages of documents produced include many specific elements of technical and scientific analysis, supported by sociological analyses. Yet important weaknesses must still be corrected:

– The information remains difficult to interpret and use, and very few rigorous and pedagogical systemic analyses have addressed the questions of regular citizens about the possible health impacts over different time horizons and about the various technological solutions (costs/benefits, advantages and drawbacks);

– Nor do we have access to any kind of analysis grid for assessing risks (one allowing comparisons of nuclear waste, industrial waste, the climate, biodiversity, etc.) posed to future generations, a long-term prospective analysis of societies, or a serious ethical reflection;

– Lastly, public officials should have greater ability to stabilise a coherent strategy over time and to oversee industrial management and operational implementation.

c) Needed improvements to the institutions that manage cooperation and controversies, need to reinvent the role of the State

To address these weaknesses, we believe it is necessary to work on two fronts simultaneously – two fronts that are all too often seen as oppositional, even though they are, on the contrary, profoundly complementary if our goal is truly to be able to act to preserve public goods (climate, biodiversity):

– First, restore the State's ability to play its central role in reviewing scientific and technical submissions, in drafting strategy proposals for the medium and long terms, in managing the industrial implementation of policy decisions, and in guiding long-term prospective thinking about the risk analysis grid and forward-looking studies of societies. Public authorities and citizens need to be able to rely on State-run scientific and technical organisations, and State services, confident that they have the necessary competencies and broad enough remits to be effective. A strong State apparatus can be an asset to democracy if it serves institutions that promote participatory and transversal democracy;

– Avoid confusion between levels of logic in the functioning of the democratic institutions tasked with managing disputed universes, levels that must be considered separately through institutions that are differentiated and function in a way that is adapted to each:

• The level of multidisciplinary scientific and technical expertise that includes the health dimension, and which must be strengthened via truly transversal work that addresses the questions posed by citizens: what danger do glass packages represent due to external radiation after 300 years, 1,000 years, and 10,000 years? What kinds of limitations do potential geologies place on waste storage? What is known about clay's capacity to retain the most radiotoxic radionuclides after 100,000 or 1 million years? The information exists to answer these questions, but scientists and experts need to be in a position to present it clearly;

• The level of transversal expertise in the area of risks, prospective analysis and ethics to inform the conversation about risk analysis grids and our long-term responsibilities, which must be invented;

• The level of industrial and operational governance of projects like Cigeo, which must be clarified and simplified;

• the level of consultations with stakeholders, at local and national scales, which must be clearly separated from transversal expertise and operational governance;

• And lastly, the level of the political process for creating a long-term strategy and managing the four aforementioned levels, organised around Parliament (OPECST) and the executive branch, knowing that a better-organised State apparatus with all the requisite competencies is lacking.

The two levels of transversal expertise (scientific-technical-health and prospective-risk-ethics) must seek to conduct their inquiries with a level of rigour worthy of the scientific method, comparing different viewpoints from different disciplines on the same subject or the same problem, and seeking to suspend (epoché) interests related to ideologies, economics or power.

Scientific communities are used to enforcing this rule in each discipline, demanding that theories (and reasoning) be coherent and comparing them to experience, in a context where this suspension is of course easier to practice due to the technical nature of disagreements. These are new ways of working and cooperating that must be experimented with, which is another reason why there needs to be a crystal clear distinction between this level of transversal expertise and that of consultation-direct dialogue with stakeholders, which by nature are interests of ideology, economics or influence for present generations, while ensuring that information is actively exchanged and that questions are answered by both sides.

GENERAL CONCLUSION

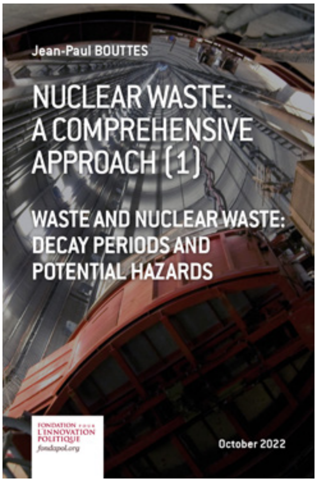
This survey has in our view made it possible to affirm that waste is not an obstacle to the development of civil nuclear power, but can, on the contrary, be an asset for the technology. Solutions exist or can be developed to protect current and future generations as well as the environment from risks that are clearly identified. The potential geologies exist and do not represent a constraint (from a technical standpoint) for the continued use of civil nuclear in France (or elsewhere in the world), on timescales of a few centuries, including with an open fuel cycle. Opportunities to reduce volumes of long-lived high-level waste have been identified, notably thanks to fast neutron technologies, which also pave the way for the use of considerable energy resources for the production of carbon-free electricity over the very long term and at a massive scale. Lastly, we know that storage can be counted on over the medium term, as long as societies can monitor, maintain and renew the facilities, if the decision is made to postpone the implementation of "lasting" solutions with passive safety.

It is possible to formulate these affirmations today because of the decades of R&D in geological storage laboratories, matrices, packages, engineered barriers, storage facilities, and partitioning-transmutation. We now know enough about these subjects to make a decision to build the Cigeo geological disposal facility, provided that the resources are made available for it to be completed on time, safely, and on budget. If these conditions are not met, and governance is such that the project is taken hostage by different stakeholders working toward other causes, then it would be best to store the waste safely for a few more decades and let a future, wiser, and more responsible generation use our scientific and technological knowledge to implement solutions itself.

The questions raised about the potential impacts of nuclear waste on distant future generations are not by any means specific. On the contrary, addressing them properly requires considering all the long-lived waste produced by our societies, and all the risks we are passing down to future generations. From this standpoint, it seems helpful to compare the risks associated with nuclear waste with those associated with toxic industrial waste, knowing that the latter exist in substantially larger volumes, and to draw a distinction between these local risks and risks that are global, major and irreversible for the planet, tied to climate change, massive biodiversity loss, or competition for the use of land and maritime space. Civil nuclear is, in this regard, a very dense energy, meaning it has little impact on biodiversity or land use, and related carbon emissions are very low. Moreover, it produces very limited quantities of long-lived waste, and solutions exist for managing it. Compared to other energy technologies, nuclear can thus effectively contribute to keeping major and global risks to the planet in check while at the same time limiting local impacts. Of course this efficiency is only relevant if it can be verified that non-proliferation rules are upheld and that safety targets are met by reactors, and provided that the energy produced is economically competitive.

Fully understanding the issue of waste and successfully implementing long-term solutions for it requires democratic institutions that are up to the task: a State apparatus with competencies in the areas of science, health and industry, held accountable for the quality of its assessments and the solutions proposed to ensure that the expectations of citizens are met and the interests of the country served; institutions with open-ended expertise engaging in interdisciplinary research into scientific, technical and health matters as well as questions of ethics, prospective analysis, and risk analysis grids; the ability to ensure operational governance of State-run industrial projects in an efficient and professional way. These institutions should participate in consultations with stakeholders representing local interests and groups of activists, and support the policy decision process, while making clear their independence through their composition as well as their ethical rules and modes of functioning.

Nuclear waste is a remarkable example of the issues associated with the long-term opportunities and risks resulting from the massive use of scientific and technological innovations. When democracies address such major problems, they need to be able to rely on collective inquiries that allow citizens to share the same basic health-related, scientific and industrial data, and to debate the expectations of future societies as well as our responsibilities. To conduct such collective inquiries in the areas of the climate, biodiversity, pandemics, the consequences of biotechnologies, nanotechnologies or artificial intelligence, we must improve our institutions and invent new ways of participating in democratic life, relying on institutions of participatory democracy that are separate (transversal expertise, consultation between stakeholders, industrial governance) and on a State apparatus that is accountable and has access to the required skills. The most lasting and crucial elements of the legacy we leave to future generations will undoubtedly hinge on the quality of these institutions and the inspiration of our practical wisdom.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A COMPREHENSIVE
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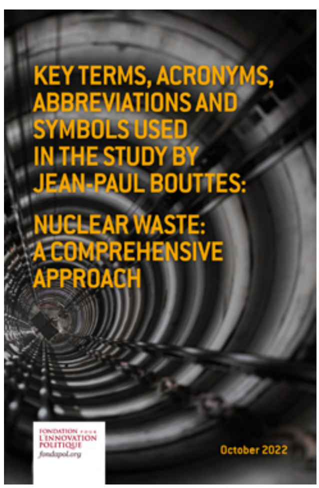
KEY TERMS, ACRONYMS,
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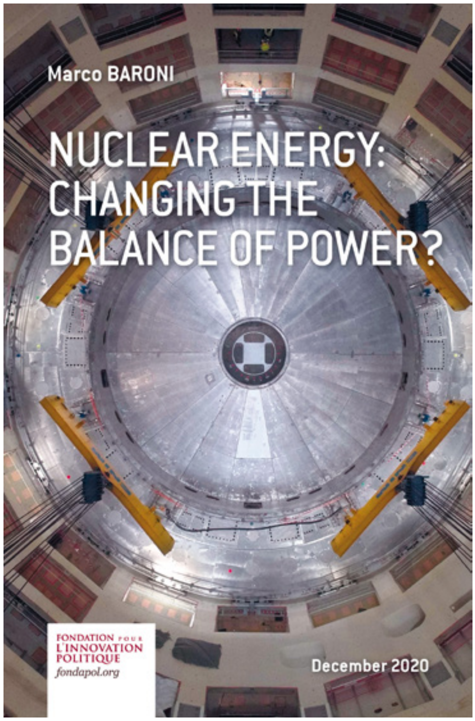
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NUCLEAR WASTE: A COMPREHENSIVE APPROACH (4)

WASTE MANAGEMENT: THE ROLE AND COMPETENCIES OF THE STATE IN DEMOCRACIES

By Jean-Paul BOUTTES

Different solutions exist for managing nuclear waste and protecting future generations over the very long term, though the difficulties encountered in implementing them should not be underestimated. These solutions require the existence of a State that is efficient and has the competencies to produce long-term prospective analyses to understand the issues facing the nuclear system, and the operational competencies to manage large-scale industrial projects like Cigeo. A look at the history of debates around nuclear waste in France also makes clear that the functioning of our democratic institutions needs to evolve considerably to better address this type of topic as well as complex subjects like climate change and biodiversity. These institutions must rely on scientific and technological expertise from different disciplines and be able to incorporate "prospective" and ethical resources in seeking to promote the general interest rather than the goals of partisans or activists. This is an invitation to invent new democratic institutions to reflect the major technical and industrial challenges that future generations will face.

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