Framing Prototypes: The Fast Breeder Reactor in France (1950s–1990s)

Arthur Jobert and Claire Le Renard[1]

This paper considers a crucial moment in the innovation process: the shift from a research phase to an industrial phase. The empirical study examines the development in France of Fast Breeder Reactor technology (FBR), from the 1950s to the early closure of the Superphénix plant in 1997. A turning point occurred in the late 1960s, when several European countries judged that the FBR technology was a promising electricity generation technology that would soon be mature for commercialisation, in a context of technological nationalism and future energy scarcity. In this paper, we analyse how the framing of the resulting prototype as "industrial" entailed an impact on decisions during the three decades that the project lasted. Aiming at describing the project actors in action without judging their decision-making processes, we use the 'framing' concept preferably to other approaches such as 'path dependency'. This concept choice is the subject of the discussion.

Keywords: nuclear technology, framing, prototypes

Introduction

From a STS perspective, the process of innovation is a temporal one, uncertain and contingent; it is driven by actors who work to find a place for their innovation in a social and economic context which might evolve. A crucial moment in this process is the shift from a research phase to an industrial phase. To bring their projects to the industrial phase, innovators have put their hopes in hybrid objects who must on the one hand, demonstrate the maturity of their technology but, on the other hand, can still be improved before they enter the market. These hybrid objects are given ambivalent names such as 'pilot-series', 'industrial demonstrator', 'industrial prototype'. Based on empirical work dealing with the French Superphénix, this paper discusses how *framing* a prototype as industrial is not only a matter of rhetoric; it may have an important impact on the trajectory of an innovation. 'Framing' will be used here as "a notion which grabs the perceptual lenses, worldviews or underlying assumptions that guide communal interpretation and definition of particular issues" (Miller, 2000: 212).

The *Superphénix* was the industrial prototype of the technology of Fast Breeder Reactors (FBRs); using neutrons in a "fast" regime, this specific nuclear technology was able to "breed" or regenerate fuel while using it. From the 1950s until the 1970s FBRs were being developed in many countries, in the expectation that they would provide a nearly inexhaustible source of electricity, needed to fuel the rapid economic growth of the post-war years. The development of a fleet of commercial fast breeder reactors was therefore considered by many as the logical end-point of a viable nuclear programme. However, the use of neutrons in a "fast" regime meant using a molten metal as a coolant. Sodium was chosen because of its thermal conductivity; it is nevertheless known for its reactivity with water and oxygen. With such features, Fast Breeder technology was to become an object of international competition, technological development, visions, and risk debate.

Approaching a controversial project: Our methodological choices

The history of Fast Breeder technology in France, and of Superphénix in particular – a reactor which was stopped earlier than planned – is a controversial one, and took place over time. Conducting a research devoted to such an innovation supposes taking methodological precautions. There is then the considerable risk of taking side in the controversy or writing history backwards (presenting the failure as predictable or even inevitable). As an answer, we want to state that a methodological stance designed to avoid both these pitfalls enabled us to add new perspectives to the existing research.

Much has been written on this project, be it in the 1970s before and during its construction, during the operation years from 1985 to 1997, or afterwards, when diverse accounts of the project tried to record its history and the lessons learnt. A great variety of primary and secondary sources can thus be found in media coverage, in "grey" literature (expert reports, parliamentary hearings...) and in academic or para-academic publications, a selection of which can be found in the references section of this paper. The main part of this literature contributes to the controversy, some authors highlighting the "failure of FBRs programmes" (see Finon, 1989), other authors in the contrary envisioning the irreplaceable role of FBRs in the future energy supply system and pleading for the continuation of the Superphénix (Vendryès, 1997).

The first methodological pitfall of researching causes for the early shutdown terminating the innovation trajectory of Superphénix would be to explain it by the very beginning. In Spring 1998, after the decision to permanently close the Superphénix was taken by the government, the French Parliament conducted hearings, allowing the concerned parties to express their controversial views. The report following these hearings stressed that the causes of the premature end of the plant were to be found at the very beginning of the industrial prototype: "the decision of creation was taken without transparency, basing on alarming forecasts, for a plant whose role appeared in the end to be fluctuating over time" (Bataille, 1998). Building an explanation on this form of evaluation puts us at a major risk of history being written by the victors. As Rip and Kemp (1998) write, we cannot analyse the trajectory of an innovation as if: "the direction of technological development was determined by the actual paths and the expectations of what could be next steps [...]. Our retrospective idea of steps in the direction of the situation as we know is irrelevant". Therefore, we tried to avoid rereading the history of the technology on the basis of its developments which were known to the researcher but unpredictable for the actors in the on-going project, and we aimed at depicting how the Superphénix was framed as an "industrial prototype", and what this specific feature – being industrial – meant for such a prototype, associated with solid expectations and new constraints.

In this respect, Bruno Latour's seminal *Aramis or the Love of Technology* (1996) was of great importance to our work. This book traces the history of a public transport project called *Aramis* which was intended to serve the south of Paris with the combined advantages of rail transport and individual cars, but which never reached the commercial stage. Above and beyond a case study, this work offers lessons on the factors for success or failure for such innovative projects, along with a methodological stance from which to talk about the past from the point of view of the researcher's situation in the present.

To avoid the pitfalls evoked above, Latour (1996: 6) suggests "going to see everybody who's being criticized and blamed" by applying a methodological principle of benevolence: the sociological standpoint consists in putting oneself in the place of the actors of the project, with their own representations of the future. The narrator talks to his (fictitious) student as follows:

> Always assume that people are right, even if you have to stretch the point a bit. […] otherwise, you play the sly one at the expense of history. You play the wise old owl. […] Life is a state of uncertainty and risk, of fragile adaptation to a past and present environment that future cannot judge. (Latour, 1996: 35-37)

This obligation to show goodwill is one of the features of the method used during this analysis of Fast Breeder technology. Another feature of the research was the quest for an inside view of events, and the field enquiry lead us to meet the people who had worked on the project.

An investigation focussing on how project promoters frame their project

For Latour, and numerous researchers after him, it is thus not a question of rereading the past in terms of the present or of a form of predestination but rather of grasping the innovators in action. Our methodological choice was thus to carry out a study of the actors involved in a Fast Breeder technology project and to try to understand the uncertain process during which the innovators defend their project and make their choices. It was notably a question of identifying the moments of choice when the actors had to decide how to modify their project to meet the requirements of the time and of the strategy they were following.

The oral sources for this work were thirty-three interviews of twenty-five project actors, two experts from the nuclear safety authority's Technical Support Organisation, and six opponents or critics of the technology (experts and scientists). Among the twenty-five interviewees who had directly worked on the Superphénix project, approximately 20 % had designed the Superphénix and/or the French Fast Breeder technology development, 45 % had engineered or built the plant, and one third had operated it. We met scientists and engineers from the CEA public research agency (Commissariat à l'Energie Atomique), who developed the demonstrators or who were the decision-makers responsible for the programme as a whole. We interviewed the managers in charge of project conception and construction, be it at the CEA, in the engineering company or in the EDF (Electricité De France) plant design and construction division. The Superphénix construction manager gave us a colourful account of events. With regard to the period of operation, we met members of the plant's board of directors and members of NERSA's board of directors (*Centrale nucléaire européenne à NEutrons Rapides SA,* the European project company created for Superphénix).

The following figure illustrates the diversity of the career profile of our

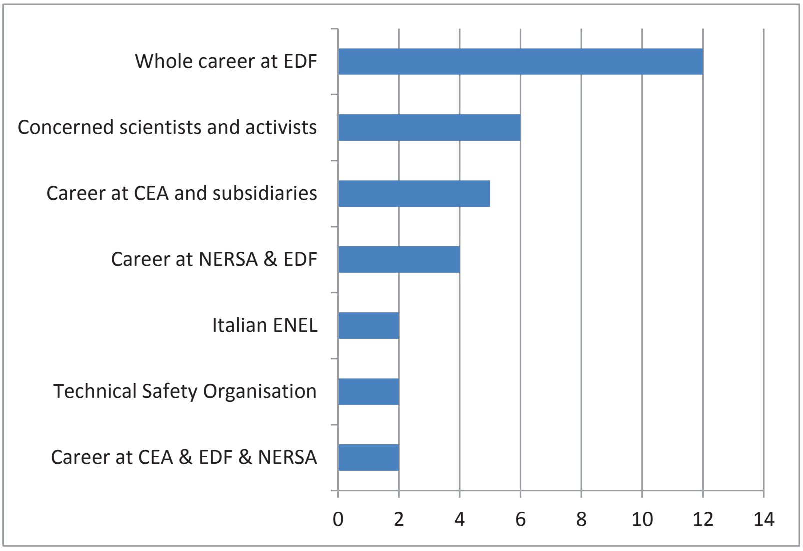


Figure 1. Position and career profile of the interviewees.

interviewees: this project brought together people coming from different professional backgrounds and cultures. Some of the project actors were involved in the first steps of FBR technology, before reorienting their careers towards other areas of nuclear power; others were involved from start to finish, devoting their entire careers to the development of the technology; finally, some worked on the Superphénix for a few years, starting and pursuing their careers in other nuclear projects.

As 76 % of our interviewees were actors of the project, we are conscious that such a dissymmetric approach of a controversial project can be seen as biased. One answer lays in the visibility of the literature critical of the project, which we carefully studied before beginning the field enquiry. Some activist organisations keep the memory of Superphénix alive, publishing their archives, press articles, and argumentations online. We met some activists or concerned scientists to record their views on the events and developments. But furthermore, we cross-checked our interviews with written sources where other stakeholders expressed their views at the time of the debates (e.g. minutes of public hearings, record of TV debate, press articles). There is no guarantee that such a process prevented us from being influenced by our interviewees. However, this cross-checking enabled us to identify critical periods, such as the debate about the re-definition of the project in the 1990s, which will be one of the topics of this paper. In fact, in a first set of interviews, the innovators tended to downplay or not evoke spontaneously this debate.

This research actually made us conscious that within such an ambitious project different opinions existed. Some actors who had the feeling their point of view had not been considered enough were glad to share their opinions in the interviews about events that happened decades ago, as well as the ones whose views had been retained for decision-making. Some of them even had kept an impressive documentation as a personal archive, in their garage or in a devoted office, which they offered us to use – this situation can be related to what Gabrielle Hecht experienced in her research about nuclear developments in France after World War II (Hecht, 2009: 18). As well as her, we can state that "most people seemed eager to share their memories, look for documents, and put [us] in touch with others who might help". And we also experienced that "some things conveyed in the interviews are not in any document, accessible or not".

A last answer lays in the very objective of this research, on which we build the point we want to make in this article. Our objective is not to conduct an evaluation, or to judge the decision of these actors on a normative basis as, in some respect, does the "lock-in" approach which implies that an inefficient technology or product "captures" markets at the expense of better products (Arthur, 1989; Cowan, 1990; Pierson, 2000). Our objective here is to better understand the rationale of actors involved in a controversial innovation project. More precisely we will put forward how the framing of their prototype as "industrial" in the late 60s entailed an impact on decisions during the 3 decades that the Superphénix project lasted.

Therefore, we will first describe the definition of the features of Superphénix as the "construction of a long chain of reasons that are irresistible" (Latour, 1996: 33). The following two parts will depict the decisions of the actors at two moments of trials, when the irreversibility induced by the "industrial" feature of the prototype made it difficult to renegotiate the project. The last part is a broader discussion of framing and irreversibility in such prototype developments.

The "Irresistible" and "Irreversible" Framing of an Industrial Prototype

The history of Fast Breeder technology in France can be better understood by a focus on its framing – in the words of Jasanoff (2005), "a conceptual language that can grapple with both continuity and change, while rejecting some of the rigidities of structure – in order to understand how policy domains are carved out from the political sphere and rendered both comprehensible and manageable". In this section, we want to depict how in the 1950s and 1960s the framing of Fast Breeder technology (FBR) as necessary in the near future resulted in the design of a "European industrial prototype" which was supposed to accelerate access to a commercial stage.

The making of FBRs as the obligatory passage point

In the context of the post-war years, as rapid economic growth entailed a rising energy demand, FBR technology was framed as the logical end-point of any nuclear programme, carrying in it the promise of inexhaustible energy. This assertion requires a little detour in nuclear physics, which we want to make as simple as possible.

Natural uranium is composed of 99.3 % Uranium 238 isotope (^{238}U) and 0.7 % Uranium 235 isotope (^{235}U). In the post-war years, several nuclear technologies were developed, among which the technology of Pressurised Water Reactors (PWRs), using the scarce ^{235}U, and the FBRs, using abundant ^{238}U. The PWR technology had been adopted on American submarines for its compactness, and had experienced more operation hours than any other nuclear technology: for this and other reasons, they were chosen as the main component of a nuclear industrial fleet in the US (Cowan, 1990), and from the 1960s on, in several European countries. The development of this technology appeared then deemed to a brilliant future, raising concerns about ^{235}U fuel scarcity that it might occasion in the medium-term.

The FBRs were then promoted as an answer to this concern: firstly, using neutrons in a “fast” regime, they could generate energy from the fission of the *abundant* isotope ^{238}U. Using therefore the energy potential included in natural uranium approximately a hundred times better, FBR technology stood above and beyond the PWR technology in the eyes of scientists and engineers. Secondly, this technology can use the Plutonium (^{239}Pu), an artificial element, as a fuel. The highly radioactive Plutonium is generated during nuclear reactions in FBRs and other nuclear reactors, when a nucleus of ^{238}U absorbs a proton released during the reaction. Thirdly, if a fuel reprocessing plants extracts fissionable fuel from the used one, the FBRs can reuse their fuel several times, thus achieving “breeding” or fuel regeneration with a Uranium-Plutonium cycle, making the energy potential close to infinite.

In the 1960s, this promise of inexhaustible energy was the horizon of nuclear development in several industrialised countries. In the terms of Latour (1996: 33), we can state that FBRs were then regarded “as the obligatory passage point that will resolve the great problems of the age”, thanks to one of “these long chains of reasons that are irresistible”. The rationale was the following: economic growth requires abundant electricity; although the PWR technology is retained as an immediate, transition technology, it remains a provisory answer, which uses the energy potential in natural uranium rapidly and poorly, raising concerns of fuel depletion; therefore, FBR technology must be developed and tend towards an industrial maturity as soon as possible.

FBR development as a national project: The irresistible alliance

FBRs were considered a strategic technology, and from the 1950s onwards, research reactors of increasing size were developed in the United Kingdom and in the United States, stimulating efforts designed to establish and demonstrate the feasibility of the technology. In the mid-50s, in an attempt to make up for lost time, France begun its first studies (Vendryès, 1997). Impetus was provided by a study visit by two CEA engineers to the USA: won over by this technology, upon their return they persuaded their hierarchy to grant them sufficient funding to build an experimental reactor in France; it was to be called RAPSODIE and reached criticality in 1967 (Vendryès, 1997). Despite having been completed four years behind schedule, Rapsodie attained full power in just three months and was regarded as a “technical success” (Finon, 1989: 159). At the end of the 1960s, research reactors also reached criticality in the USSR and Germany. The promise of abundant and inexpensive energy fostered technological developments in numerous areas in order to establish the feasibility of the FBR technology. The competition between countries regarding technological achievements served nationalistic purposes, and became a driver as well as a consequence of technology development. Conferences and academic/professional publications were arenas for international competition, as well as for the circulation of ideas, helping to create a common mindset among the experts involved (Goldschmidt, 1967).

At the same time, the exponential growth in energy requirements in the 1960s saw several countries equip themselves with industrial nuclear power. In France, as well as in other European countries, a dispute took place between the advocates of the “national” reactor design and the promoters of the American PWR. Beyond technologies, this dispute opposed arguments centred on national technological excellence vs. inexpensive electricity generation (Hecht, 2009). As they featured more operating experience as well as lower projected generation costs, PWRs were retained for the industrial fleet in the short term. In the late 60s, while the interests and views of the key actors in the French nuclear "establishment" (especially between EDF and the CEA) diverged on many issues, "the breeder reactor emerged as a source of consensus" (Hecht, 2009: 291). On the one hand, building on the experience acquired with national prototypes, it allowed the pursuit of national technological excellence – as Hecht (2009: 293) notes, "they transferred the burden of French grandeur to the breeders". On the other hand, the objective to produce cheap and abundant electricity would be met by the choice of American technology in the short term, and in the medium and long term by the "logic of a breeder future" (Hecht, 2009: 293).

FBRs became then the only remaining nationally developed nuclear technology. Fast breeder prototypes were developed as part of a long-term, national nuclear project, which would include reprocessing and a fleet of industrial 1000 MW breeder reactors (Finon, 1989: 182). In southern France, while the experimental "Rapsodie" reactor was only starting to operate, the design of a 250 MW prototype reactor was already initiated: it was to pave the way for the to-be industrial FBRs. Named after the bird which rises from its own ashes, the "Phénix" reactor represented FBR technology regenerating its fuel. With its 250 megawatts of electricity, it provided the same power as the coal-fired plants of its time. It reached criticality in 1973 and was acclaimed as a technical success: France had made up its lost ground in FBR technology. On March 15, 1974, as the Phénix reactor reached nominal power two weeks ahead of schedule, the Financial Times entitled an article "French world lead in fast reactor technology" (Sauvage, 2009).

Combining the stakes of future energy supply with the achievement of nationalistic "grandeur", FBR development became a privileged cooperation field for the CEA and EDF: D. Finon depicts it as the "irresistible logics of an EDF-CEA alliance" from 1970 on (Finon, 1989: 169).

A project made more irreversible by its European features

Latour (1996: 154) states that "technological projects become reversible or irreversible in relation to the work of contextualisation". By the beginning of the 1970s, atomic energy agencies in several European countries (e.g. in UK, France and Germany) envisaged reactors of a capacity around 1000 MW. These full-scale reactor projects anticipated a future series reactor design which would have to be both industrial (powerful and reliable) and commercial (able to equip the national fleet and to be exportable). The electricity utilities then became key players in the development of such projects, making them reversible in some countries (the British project was stopped in the late 70s, see Le Renard et al., 2013), but contributing to make the project more irreversible in our case study, through the commitments that the French state took vis-à-vis its foreign partners.

In the 1960s, the European community and its nuclear research programme Euratom had attempted to foster the development of a European 300 MW FBR prototype, with limited outcome. But this initiated a European cooperation which would succeed in the next step of the programme, the 1000 MW prototype (Giesen, 1989). Three electricity utilities (the French EDF, the Italian ENEL and the German RWE) had initiated collaboration as early as 1970 to envision a common FBR industrial prototype in order to share costs and operating experience. The deliberations amongst the utilities, the CEA, and the French government resulted in the 1200 MW Superphénix project in the south of France, and its German counterpart, SNR 2, whose construction was to start shortly after that of Superphénix (Marth, 1993). This larger size was comparable with the 1300 MW PWR plants developed at that time. In the same way that the development of Phénix had taken place during the worksite of Rapsodie, in the early 70s, the developments of the Superphénix project were begun in parallel to the Phénix worksite, in order to maintain engineering skills permanently working on the new technology. Beyond its name (an 'extended' Phénix), several significant characteristics of the project development changed with Superphénix, hence marking the shift of FBRs from an experimental to an industrial era:

- The owner of the Superphénix project was a limited company (NERSA) created with equity from several European electricity companies. The EDF held 51% of the capital, ENEL 33%, while the remaining 16% were owned by RWE;
- The CEA licensed the FBR technology to Novatome, an *ad hoc* subsidiary, which would be able to meet orders for future FBRs on an international scale.

This double choice of creating an *ad hoc* company that would from the beginning include European partners was representative of a new way of managing large technological projects. During the same period, the commercial failure of the Concorde triggered the development of the "Airbus model" (Muller, 1989). In the context of increasing competition with large (especially American) multinational enterprises, the aim to develop industrial products that may be commercial on a large scale was added to technological achievement. Bringing together European partners was therefore a way to share the risks and competitive advantages, as well as to expand the potential markets. The agreements to form the European company NERSA provided that the electricity generated by the new plant was to be returned directly to the countries involved on a *pro rata* basis, in line with their levels of participation: the search for a site with the required physical and geographical qualities led to the industrial prototype being located at the centre of the Lyon-Genève-Chambéry triangle (i.e. at a reasonable distance from the Italian and German borders), near the village of Creys and the hamlet of Malville.

As the plans for the creation of the NERSA were well underway, on 13 December 1972, a parliamentary debate was held concerning a bill that established an exception to the 1946 law on the nationalisation of the electricity sector, and would instead allow the creation of enterprises in the domain of electricity that would carry out in France "an activity of European interest". The creation of European companies was contested by the trade unions and by a part of the opposition (especially the communists). The critics feared that the entry of private interests in the energy sector would work in the same direction as the choice of the "American" PWR technology. But the project was then promoted as French technology development, as well as providing energy independence for the nation. The fact that the project was also European did not contradict this idea, quite the contrary: as was the case in many other areas of European politics, the project was seen as a "continuation of France through other means". The project's legitimacy was assured by the political consensus on its objectives both at the same time national and European, commercial and of high technology.

However, the term "industrial prototype" conveyed an ambivalence which was to endure throughout the project. The project was industrial because of its ambitions and the way it was organised. It was a prototype because its role was to test a new technology – at that time no FBR of that size had ever been built. Many of the elements were innovative, either in terms of size, or in terms of the options chosen – some as a continuation of Phénix and others through the European dimension and the experience of collaborating countries.

Work on the Superphénix industrial prototype lasted almost a decade, from 1976 to 1985. The project managers had to overcome numerous difficulties: in creating a 'first in the world', they were constantly facing new technical challenges, many of them related to handling the huge components of the plant. But these actors were sustained by the conviction that they were working on higher objectives and priorities: making a virtually inexhaustible source of energy available to mankind. Parallel to the construction of the industrial prototype at Creys-Malville, the engineering teams in Lyon were preparing for the next stage, that of defining the characteristics of the series of plants based on the Superphénix, so as to be able to rapidly launch a fleet. They were also investigating future sites.

During this decade of the project, objectors to the project criticised the choices which had been made on two fronts: criticism of the technology chosen and criticism of the industrial option.

Criticism of the industrial prototype aspect of Superphénix came from scientists and concerned individuals in the nuclear sector. They felt that FBR technology had not been sufficiently tested to be ready for the industrial stage, and that it would be wiser to build a smaller plant designed for research or development purposes. They developed this argumentation in documents published by trade-union or political parties (Parti Socialiste, 1978: 35).

The other criticism was radical; it concerned the very structure of the promise of inexhaustible energy contained within the development of FBR technology: the regeneration of fuel meant building a huge fleet made up of PWRs, FBRs and fuel reprocessing plants and keeping them all running over the very long term. For the decision-makers of the time, facing future scarcity of fuel, this was exactly what was needed; for the critics, it was unacceptable. FBRs regenerate their fuel in the form of plutonium, which is both reactive and toxic, and certain isotopes of which can be used for military purposes. Opposing the very principle of this technology, critics organised demonstrations, the most important of which took place in 1977 and led to the death of one demonstrator.

However, although the growth perspectives for energy demand which had led to the creation of Superphénix seemed to have properly stabilised, as from the mid-1970s the contextual aspects changed, one after the other: in 1976, pluralist commissions including academic experts both in the United Kingdom and the United States evaluated the need for FBR technology and its costs and risks. The gradual drop in energy demand, due to the economic slump following the oil crisis, was beginning to chip away at the urgent nature of building an FBR fleet. In fact, nuclear reactor orders in the United States had been drastically reduced in the mid-1970s and brought about a major downward revision of the growth forecasts for nuclear power throughout the world. In reports within their respective countries (Flowers, 1976; Keeny et al., 1977), the evaluation commissions recommended postponing projects for industrial prototypes, because the fast-breeder fleet was no longer envisaged over the short term. Scientists fed these points of view to French associations critical of the project.

The objectives of an initial industrial demonstration nevertheless remained preponderant in the debates which took place over this decade. The government was a key player in the decision-making, and the promise behind this energy technology justified France continuing to develop it, as can be seen in a statement made in Parliament by the minister of industry in June 1977: “it would be very dangerous to abandon this fast-breeder project due to pressure from a small group of people who may be well-informed within their own fields, but who in any case have a poor grasp of the national context in which our energy policy is rooted!” (Journal Officiel, 2 June 1977, quoted by Finon, 1989: 202).

The debates on FBR technology organised by the Europe 1 radio station and the Antenne 2 public television channel in 1980 were a forum for public discussion which confirmed what was at stake: President Valéry Giscard d’Estaing declared that “if uranium from French soil was finally to be used in fast breeder reactors, in France we would have energy reserves comparable to those in Saudi Arabia” (Bériot & Villeneuve, 1980). Questioned about the American halt in FBR development as part of the non-proliferation policy, the French MP and former Prime Minister P. Messmer stated in the same debate series: “the United States would prefer it if we did not maintain our advance, particularly due to the industrial and commercial advantages that it offers us” (Bériot & Villeneuve, 1980, quoted by Finon, 1989: 198).

In France, there was no question of closing off the option that this technology represented: Superphénix was already being built as an industrial prototype, and the principle of commitment to the industrial series envisaged by the CEA and EDF’s plant design and construction division was validated. Meanwhile, from 1979 on, EDF’s general management postponed the decision to commit to the industrial series in order to have one full year of feedback on the operation of the Superphénix reactor (Finon, 1989: 214-218). The argumentation was rooted on economic assessments which compared the competitiveness of FBR technology with that of other types of energy production, the assumptions for the future cost of Uranium being less favourable to FBR than previously.

Pursuing the Industrial Demonstration at the Cost of Technical Flexibility

Confirming the industrial dimension of Superphénix

In 1985, fuel was loaded into Superphénix’s core. After ten years of construction, the Superphénix industrial prototype was finally completed and began its industrial operation. To this end, the small project company NERSA had signed a contract with national electricity company EDF. The Superphénix industrial prototype benefited from the experience and standardisation of the operational nuclear fleet, and as such, personnel would be employed in accordance with the standards of EDF’s organisation charts.

In 1986, the electricity generation unit of the plant was connected to the grid. Yet that same year, several events took place which were to radically change the way the future of energy and the relative value of the different sectors of production were envisaged.

1986 was the year of the Chernobyl accident, which impacted Superphénix in many ways: for the very first time, Chernobyl brought to life the reality of the dangers of a nuclear accident, and, more broadly, marked entry into the "society of risk", according to the eponymous work by Ulrich Beck published a few months later. Many countries suspended their nuclear programmes, reducing even further the foundation of the discourse on the depletion of uranium which had justified development of FBR technology. Among these countries was Italy, which nevertheless maintained its shareholding in NERSA. The actors concerned by the risks with Superphénix saw their case strengthened by a serious sodium fire in a solar power plant in Almeria in Spain, which also occurred in 1986. Lastly, 1986 was the year of the oil counter-shock, which marked another turning point in the way the future of energy was envisaged: energy seemed to be abundant and cheap, and the energy-saving measures which had been recommended since 1973 fell into disuse, as did new technological developments. Long-term concerns relating to the Earth's finite resources were pushed onto the back burner.

Finally, Superphénix was the precursor for a long-term series at a time when people were no longer interested in the long term: *First Of A Kind … without a kind*, it now had to operate as an industrial plant within the EDF fleet, with the objective of providing a return on investment and of continuing to demonstrate the technology, for what was now the distant future.

Over the lengthy term of the project, whilst the context had changed, the industrial objectives remained the same: they were reflected in the size of the plant, in its system of multi-country governance and in its integration into EDF's operational fleet.

Such a nuclear project has a time constant of several decades. The project's engineers remained convinced that they were working on a technology for the future, one which might replace the temporary PWR technology: even if temporarily the conditions did not appear to be ripe for the launch of a fast-breeder fleet, they had to continue to develop existing skills so as to be able to use the technology in the future. At the end of the 1980s, European countries combined their efforts to design the EFR, the European Fast Reactor, which would capitalise on the experience gained with Superphénix. An article in an IAEA bulletin which set out the global situation for developments in 1989 stated: "In Europe, it is now considered that [FBR] plants would begin to replace the decommissioned PWR plants after 2010, in competition with the then-available advanced PWRs." (Golan et al., 1989) The status of the "industrial prototype" without any planned series in the short term was becoming difficult to justify: what was Superphénix a prototype for? Did the characteristics of the plant really make it "industrial"? At a moment when these strategic questions were asked, an incident occurred on a critical part of the plant, which lead project managers to make a decisive technical choice.

Translating the industrial framing into a concrete decision

In March 1987, a sodium leak occurred in the fuel storage "cylinder" tank. To understand the negotiations and the choices made, we need to take a closer look at this technique:

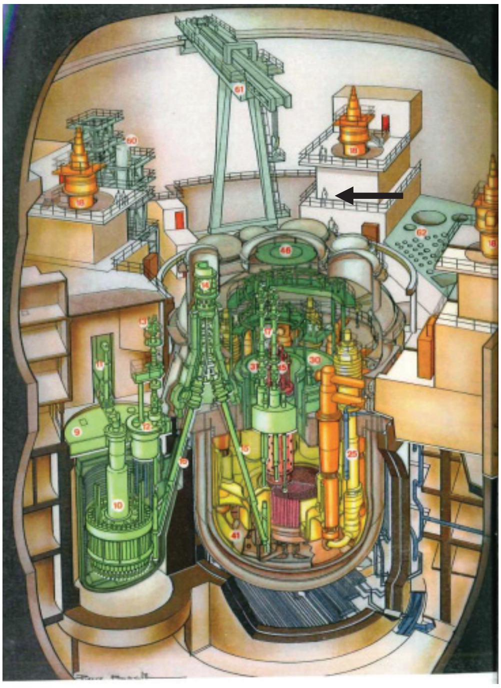
The Phénix plant and associated reprocessing facility had demonstrated the possibility to recycle the fuel, and thus, on a small scale, to fulfil the promise of energy autonomy inherent in FBR technology, on the basis of a "short cycle" involving Uranium and Plutonium (Sauvage, 2009). The Superphénix fuel cycle was to be the same "short cycle" which had been validated with Phénix, and the relevant technical device was very similar, implying a fuel storage cylinder tank. The "short cycle" consists in discharging and renewing a fraction of the fuel contained in the core of the reactor (one third or one quarter) during relatively brief stoppages. The fuel transfer has to take place within the sodium, preventing the fuel which was in the sodium to be brought into contact with air or water. When leaving the core, this fuel gives off a very large amount of thermal power; it must thus cool in order to reach the thermal power designed for the reprocessing facility, five times lower than its level when leaving the core.

As a Novatome document (1981) states:

> "The fuel handling system comprises installation and equipment provided for
>
> - Simultaneous fuel loading and unloading by means of two sloping ramps, leading from a rotating transfer lock to the reactor on one side and to the fuel storage [cylinder tank] on the other,
> - Storage of spent fuel in a sodium-filled decay [cylinder] tank before being sent to the reprocessing plant. The decay heat is removed by two independent sodium circuits connected to air-coolers."

In the same Novatome document, the following cutaway view shows the rotative device or "carrousel" (10) inside the fuel storage cylinder tank (9), which enables the operator to select and handle any fuel subassembly. This possibility to separately handle the subassemblies is useful for purposes such as research on assemblies or fuel recovery. These handling activities can take place during the operation of the plant, providing flexibility.

Benefiting from the experience acquired with Phénix, this fuel handling system was optimised in the available space and included in the concrete. The sodium leak in the fuel storage cylinder tank was as unexpected as improbable. The choice of the steel nuance used for the tank, which was different from Phénix, was held liable for the leak. Questions about what repairs were required led to a reopening of discussions on the purposes of Superphénix, as it was technically very difficult to replace the tank with an identical one. The impossibilities of the technique meant that it was necessary to negotiate and lower the objectives of the plant, or to come up with a technological "detour" (Latour, 1996: 215) which would make it possible to remedy the insufficiencies.



Picture 1. A cutaway view of the fuel storage cylinder tank, reactor vessel, and fuel handling system (Novatome, 1981). The arrow indicates the figures on the upper part of the reactor vessel, allowing one to imagine the true dimensions of the plant.

The decision to replace the defective tank with an identical one was rejected: according to some interviewees, it was technically impossible or excessively expensive; according to others, it would have required a very lengthy stoppage. But due to its industrial framing, the plant was expected to generate electricity for the partners of the project, and not to be offline for a long time, as a non-finalised prototype might have been.

The storage tank was replaced by a fuel transfer unit which fulfilled certain fuel handling functions, but not its cooling: the fuel then had to cool down within the reactor core itself. This implied an operating mode known as "long cycle", where the reactor must remain stopped for six months for cooling, in order for the used fuel to be discharged and for the new fuel to be loaded. It was no longer possible to renew just parts of the core, and the "long cycle" meant that an entire core had to be burned during each cycle.

The choices made during this period were a consequence of the industrial framing of Superphénix, and they "in-scripted" it even more in the technology: the fuel storage tank was not the only thing to be dropped. The project abandoned a certain flexibility of operation, characteristic of research plants and prohibited by the new system; it also abandoned the idea that the prototype should perfectly reflect the future series, feeling it to have been pushed back into the long term. The use of the fuel transfer unit lengthened Superphénix's operation cycles and made them less representative of a future fleet: "for Superphénix it wasn't very serious, but for an industrial fleet it would not have been viable", explained one of the actors. In his view, in 1988, within a context of discussions on the utility of fast-breeder technology, there was no longer any urgency to demonstrate the feasibility of the exact prototype of the industrial series.

This moment of opening-up and discussing the technical choices to be made whilst facing increased constraints led to a confirmation of the industrial nature of Superphénix and of its mission to produce electricity on a large scale as part of the operational nuclear fleet. Questions concerning replacement of the fuel storage tank were addressed by internal project decisions or by interaction between technical experts to decide what type of work had to be done. The safety of the plant had been controlled throughout the process, and the technical options had been discussed with the Ministry Control Service for Safety of Nuclear Installations (SCSIN) and its Technical Support Organisation.

A Difficult Reframing towards Research: The Weight of Irreversibility Induced by the Industrial Framing?

The plant restarted in April 1989, but another incident occurred one year later: in July 1990, pollution or oxidation of the primary sodium was detected and led to stoppage of the plant. This pollution was due to air entering the argon circuit[2] through a defective membrane in an auxiliary circuit. The stoppage lasted for four years, with the plant only receiving authorisation to restart in August 1994.

This unforeseeable stoppage gave rise to a period of intense controversy. Among multiple subjects of concern, the main issues of the controversy were the safety of the plant and the objectives of this industrial prototype. Both were publicly discussed in official arenas, which had been created in the 1980s after changes in the political majority. The two issues were closely linked, but for the purposes of this article, we will focus on the attempts of reframing the plant's objectives. We'll just briefly state that the safety issues were addressed by interaction between technical experts and led to major works being carried out ; in the 1990s, they were also discussed in official and public arenas.

In fact, as the perspectives for uranium depletion were called into question, the 1990 technical incident opened a broad public phase of project reassessment with regard to the new energy context. This reassessment involved debates between experts on forums or via official reports. Between 1991 and 1998, 14 official public reports examined the project from different standpoints such as: its safety, its objectives and purposes, its costs, or its contribution to the knowledge of industrial FBRs. Seven of these reports originated in parliament and gave rise to public hearings.

Thus in May 1992, the OPECST (Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques / Parliamentary Office for Evaluation of Scientific and Technologic Choices) organised public hearings on the possibility of restarting Superphénix and the future of fast-neutron reactors [FBRs]. Some long-standing opponents argued that the plant should purely and simply be shut down, given the technical difficulties which had been encountered and the absence of any FBR industrial programme for the foreseeable future. Supporters of the project recommended restarting the plant in order to keep the door open, to gain technical knowledge through operation and, by producing electricity, to engender economic gain from the investments made (Birraux, 1992).

This argument in favour of a restart was accompanied by a new proposal. The idea was to take advantage of the flexibility offered by the operation possibilities of the plant, designed to produce electricity by breeding or burning. The plant would thus become a "plutonium incinerator". This idea was nothing new, as since the outset, the relative flexibility of FBR technology and its capacity to operate as breeder or burner, had been arguments regularly used to support the scientific and energy utility of this technology. For instance, Golan et al. (1989) argued: "There is no better way for 'storing' and utilizing plutonium than in an LMFR[3] plant. The recycling of plutonium into LMFRs would also allow "burning" of the associated extremely long-life trans-uranic waste [...]. All these perspectives strongly suggest that we should maintain the momentum for LMFR development and demonstration until at least commercially viable LMFR standard designs are fully licensed and demonstrated. [...] The LMFR is the only proven technology capable of providing virtually unlimited new fissile material from the world's ample supply of depleted uranium, low-grade natural uranium, and thorium resources to fuel the increased need for nuclear power in the next century and beyond." In the early 1990s, this idea found a certain echo following the fall of the Berlin wall, when the West was concerned about the future of the stocks of nuclear weapons from the Soviet empire.

Some people, and the Minister for Research in particular, supported this argument by recommending that the plant be used to carry out experiments on the destruction/transformation of radioactive waste as part of an ambitious 15-year national research programme initiated by a law passed in 1991 (Barthe, 2006). However, this redefinition of the purpose of the plant was challenged. Doubts about the real scientific potential of the plant were expressed during the debate. The plant was deemed to be too large for a research facility, to be unwieldy (particularly due to the loss of the fuel storage cylinder tank) and to be unsuitable for research missions (unlike Phénix). At the end of 1992, the report by the group of experts, led by Minister for Research Hubert Curien (1992), cautiously concluded that there was an opportunity for a research programme which would complement those being carried out elsewhere.

The conclusions of this cautious report were consistent with a certain reluctance on the part of the project promoters to reframe their project with a scientific vocation. They still had the firm conviction that the plant was viable and could fulfil its primary vocation - that of producing a large amount of electricity in industrial conditions. As they confirmed during the interviews, as far as they were concerned, their priority remained to achieve the technical and commercial demonstration of electricity generation by FBRs. In their views, technical features were obstacles to a conversion to research, and the loss of the fuel storage cylinder tank as well as the size of the plant offered little opportunity for carrying out experiments.

But obstacles were also institutional and economic. On an institutional level, France (through the project company) had signed an agreement with its partners for the development of a commercial plant, not a research facility. The European partners were not keen on the suggested redefinition. In 1994, when the research missions took concrete form, they accepted contractual changes to take this reorientation into account. The initial commercial vocation of the plant also affected the way its economic value was assessed (Le Renard & Jobert, 2013). In France, the level of investment was criticised with regard to the amount of electricity actually produced, and the European partners were also concerned about return on investment. For the project company, it was therefore important to be able to continue to produce electricity under the best possible conditions.

At the end of these initial consultations, the government laid down the conditions for restarting the plant. Among these conditions was the organisation of a new public consultation process (*Enquête publique*) which led to new public discussions in 1993. During these debates, the project promoters stressed the "versatility" (*polyvalence*) of the plant, its capacity to operate as "breeder" or "burner", rather than its vocation for research.

The cautious wording of the 1994 government decree authorising the plant to restart reflected this hesitation to give the plant a research mission:

> Given the prototype nature of the plant, it will be operated under conditions which *explicitly* favour safety and the *acquisition of knowledge, for the purposes of research and demonstration*" (decree dated 11/7/94, article 3, emphasis added).

In 1996, while the plant was operating satisfactorily, a new commission was asked "to assess Superphénix's capacities as a research facility" (Castaing, 1996). In turn, it gave a mitigated opinion, concluding that there was the possibility that the plant might make a moderate contribution to research in the area of waste management. A physics researcher (long-standing opponent of nuclear power) resigned from this commission and in an open letter expressed his disagreement concerning the utility of continuing operation for research purposes. At the same time, opponents took legal action and succeeded in establishing an inconsistency between the new objectives of the plant as defined, and these which had been set out in the 1992 file supporting the public consultation process. On the 28th February 1997, when Superphénix was stopped for scheduled maintenance, the 1994 decree was revoked. A few months later, on the 19th June 1997, newly elected Prime Minister Lionel Jospin announced in his inaugural speech to the Parliament that "Superphénix will be abandoned"[4].

This decision opened the way for multiple interpretations of the plant's future. This early termination after one year of perfectly satisfactory industrial operation in 1996 shocked those involved in the project. As far as they were concerned, the decision was premature, because it was not possible to judge a project if it had not been allowed to run its term. For the more critical actors, it was the "natural" end for an overly ambitious project to rapidly move from experimental models to a commercial model. From a more neutral standpoint and using terms borrowed from science studies, one might say that at a given point technology had no longer been able to hold together all of the project's contradictions (Latour, 1996: 232) and in particular those between the commercial vocation and the technological demonstration.

Discussion

As Bruno Latour (1996: 228) states: "Mechanisms cope with the contradictions of humans". Coming back to this assertion appears to us of importance, at a time when the energy policy seems to rely more and more on "industrial demonstrators". We want to broaden our argument to those hybrid objects who must on the one hand, demonstrate the maturity of their technology but, on the other hand, can still be improved before they enter the market. These hybrid objects are given ambivalent names: "pilot-series", "industrial demonstrators", "industrial prototypes".

A difficulty of such technical objects, be it small devices or imposing plants, is to combine the requirements of research with these of industrialisation. They are the inheritors of a series of expectations (Borup, 2006; Bakker, 2011) which gave shape to the research from its first steps; in turn, the research deemed as successful progressively enabled the realisation of bigger prototypes.

The "prototype" development is linked to the research process. If the innovators succeed in making their project a synonym for solving the great problems of the age, through activities of 'enrolment' and 'translation' (Callon, 1986), the research will be supported. In the 1950s and 1960s, FBR technology was developed because it carried with it the promise of virtually inexhaustible energy. This promise of being freed from issues of fuel supply and resource depletion answers one of the biggest issues of energy forecasting. This is the framing for the development of the technology as a long-term horizon.

Such a challenge justifies investing in technology development and setting up prototypes of increasing size in order to overcome the engineering difficulties which come between a promise and its realisation. Each promising prototype makes it possible to continue efforts to develop this technology, thanks to positive technological feedback as well as positive economic and political feedback. In the conceptual tools of "path dependency", this can be described as "increasing returns" (Pierson, 2000). These scientific and technical successes strengthen the promoters' convictions, envisioning a hegemonic presence of their technology in the future.

Meanwhile, at this stage, the development possibilities are open, as the prototypes benefit the protected framework of a "research" status. The economic constraints are those of a research budget, not of an assessment of competitivity. The project can be improved, devices can be modified, Phénix can be stopped for a certain period of time for this purpose, and this is regarded as normal. The material flexibility of the plants equals the flexibility in the discourses regarding the future uses of the technology.

In the late 1960s, in a climate of future energy scarcity and technological nationalism, several European countries judged that the FBR technology was now mature enough for the next prototype to be an “industrial” one. Because this plant was the logical endpoint of the pathway created by the preceding developments, it incorporated some irreversibility, or “path-dependency” – yet this concept implies an ex-post assessment of an economically inefficient choice. As we aimed at describing the project actors “in action” (Latour, 1987) without judging them, we found that their decision-making processes could be better captured by the “framing” concept. Therefore, we want to further discuss how the framing of the prototype as “industrial” entailed an impact on decisions during the 3 decades that the project lasted, as it diminished its flexibility.

Framing the prototype as “industrial” supposes taking it out of its protected research laboratory and confronting it with its “users” or “clients”- and, in this purpose, forecasting what the context of the project will be, which will, in turn, shape the project. For Superphénix, the environment of an “industrial prototype” at the beginning of the 1970s was composed of: a fleet of 1000 MW reactors, which defined a size; modernity and sharing of risks achieved by European projects, which defined a project company; future export of the technology which defined a subsidiary of the CEA that would be the licensee; the aim of generating electricity in the EDF fleet, which defined an organisational model for operation, as well as concerns for return on investment; the obligation to pay back the investors with generated electricity, which defined a location in South-Eastern France. This impressive “chain of translation” describes the moment when the project took concrete form at an organisational and technical level. As the project had incorporated all these dimensions, the project managers and funding authorities were in an operational state-of-mind. The framing through which they interpreted events was that of an industrial prototype of a promising electricity generation technology that would soon be mature for commercialisation. More generally, as “industrial demonstrators” or “prototypes” represent the first step of an industrial development pathway, they translate the link with the future users as well as the commercial dimension in their material shape.

After the first incident in 1987, the project managers’ choice to replace the fuel storage cylinder tank with a “fuel transfer unit” was the concretisation of a change in the context, as the need for the technology on an industrial scale had been pushed away to the medium term. This solution also reinforced the industrial framing of the plant, enabling it to restart operation within a reasonable delay. After the second incident, the very industrial nature of the plant was questioned, and the innovators added a research programme to their operation schedule, without believing that the plant could be completely transformed (and reframed) into a research facility. The industrial framing of the project had left its mark in the materiality of the plant and in its organisation: it missed the flexibility of a research project.

In the middle of the 1990s, Superphénix could thus be viewed as an industrial plant which must gain a return on its investment, or else as a socio-technical innovation which must negotiate its boundaries and its technical content in order to integrate whatever has changed in its environment. B. Latour explains cessation of the innovative Aramis transport programme in this way: the promise of industrialisation in the near future makes it possible to rouse interest in the programme but prohibits the constant renegotiation that research requires. In the research phase, technological objects are in the hands of their inventors, open to many options and can be forgiven for many of their technical problems, whereas in the industrial phase they are meant to be fit for their purposes and reliable enough to be transferred to foreign hands. In the words of Latour explaining the causes for the stoppage of the *Aramis* project (1996: 293): "But then you would have needed to acknowledge that this was a research project", and "Oh, you do love science! [...] But technological research is the exact opposite of science, the exact opposite of technology."

In this way, considering the many industrial prototypes or demonstrators, it appears to be crucial to question the combination of the research flexibility of the prototype – leaving the future open – with the more rigid framing implied by "industrialisation" or "commercialisation". Paradoxically, this "industrial" framing understates an environment, users, legal framework, etc., that the project will meet at this stage – and this encounter could in turn require more flexibility. When an innovation has had a relatively long trajectory before reaching this stage where negotiation would be most required, it can be weighed down by the combination of the personal commitment of the innovators, institutional rigidities, economic investments and technical "scripts" introduced during the innovation – all of which might at some stage restrict the innovative actors' capacity to imagine or defend any reframing of their project.

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Arthur Jobert
Groupe de Recherche Energie Technologie Société
EDF R&D, ICAME
1 avenue du Général de Gaulle
F-92 141 Clamart, France
arthur.jobert@edf.fr

Claire Le Renard
Groupe de Recherche Energie Technologie Société
EDF R&D, ICAME
1 avenue du Général de Gaulle
F-92 141 Clamart, France
claire.le-renard@edf.fr

Notes

1 Corresponding author
2 The inert gas argon was in contact with sodium.
3 Liquid Metal Fast Reactor – an equivalent for FBR
4 http://archives.assemblee-nationale.fr/11/cri/1996-1997-ordinaire1/163.pdf