7 Making the accident hypothetical: how can one deal with the potential nuclear disaster?

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> Atomic power can cure as well as kill. It can fertilize and enrich a region as well as devastate it. It can widen man's horizons as well as force him back into the cave.
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> —Alvin M. Weinberg, nuclear physicist, testimony to the US Senate Commission on Atomic Uses, December 1945

Geneva, 1955. The first international conference of the Atoms for Peace program took place on the shores of Lake Geneva. Initiated by US President Dwight D. Eisenhower in 1953, Atoms for Peace was created, with UN patronage, to promote all the peaceful uses of nuclear technology over the world, and the conference signaled an energetic optimism. Industrial achievements, mostly American, were exhibited for the first time, harbingers of a massive use of promising energy. As the historian John Krige (2006) has shown, this was not simply a question of using a new source of energy but enabling the advent of affluence across societies, in which energy would be so cheap that the electricity meters could simply disappear. It was a far cry from the image of destruction and devastation that had gripped the world a decade earlier and seemed to signal a radical change in the trajectory of the atom.

Since the very development of nuclear power industry, the destructive potential of the atom has been made concrete. The transition from experimentation to the commercial exploitation of the atom between the 1950s and 1970s was accompanied by numerous reflections on the new risks generated by the use of nuclear energy. Of course, destruction was not the purpose of civilian technologies, but accidents, experts cautioned from the start, could occur. In particular, nuclear physicists cautioned that nuclear energy raised a new form of risk, and plant designers worked to imagine the damages that an accident might cause. This is why, at the Geneva conference, a small session addressed the issue of reactor safety, in conjunction with the issues of "industrial hygiene" and "radiation protection." Jean Bourgeois, head of the French subcommittee

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on reactor safety, suggested that, "Technical precautions are such that the probability of such an accident is extremely low, while the most pessimistic assumptions lead to extremely high damage, so that the product approaches the undetermined form 0 X ∞."[1] Thus, amid participants' enthusiasm for an expansion of peaceful nuclear applications, the proceedings of the conference reveal that, even then, mastering risk was also a good business practice: the consequences of an accident affecting public opinion could shut down the nascent industry.[2]

Proponents appeared truly challenged by the effort to master this new form of risk. As experts claimed that an accident was extremely unlikely, the development of nuclear energy aimed not at rendering such accidents impossible but minimising the risks to an economically acceptable level. During the same session that included reactor safety, C. Rogers McCullough, representing the Advisory Committee for Reactor Safety of the US Atomic Energy Commission (AEC) said plainly: "Of course, absolute safety is not possible and what is really meant in connection with reactor hazards is the minimization of hazards until one has an acceptable calculated risk."[3] Promising a quick and massive expansion of nuclear technology in 1955 meant promising that a still brand-new technology, full of unknowns, was a hurdle; this new type of risk and the impossibility of absolute safety challenged the nuclear industry and regulation. Five years prior, the AEC had taken a more cautionary tone: "The situation confronting the Atomic Energy Commission is one in which the danger of building and operating these devices must be weighed against the need for advancement of the technology of the field."[4] The 1945 bombings had left a deep impression, as Paul Boyer writes in *By the Bomb's Early Light* (2005), and scientists, business interests, and policymakers understood that they would need to be serious about safety if the non-military use of atomic power was to gain social acceptance. Development of nuclear power relied on the premise of safely operated power plants (Topçu, 2013), and that raised a host of debates about what constituted a sufficiently adequate level of safety in order for a proposed facility to move forward. Throughout the 1960s and 1970s, the expression "how safe is safe enough?" would be deployed regularly in the rhetoric of both supporters and detractors of nuclear expansion.

This chapter aims to examine nuclear engineers' working practices and strategies to minimise the risks related to civilian uses of atomic energy. How can nuclear energy be considered safe, in spite of its potential for destruction? How do we envision to live safely amid the new nuclear risk? While the focal case is French, it reveals nuclear development in relationship with other countries, as nuclear safety is, without question, an international domain. Understanding the French case is impossible without looking to the way nuclear safety has been treated in other countries and in the US particularly because of the transnational dimension of nuclear safety. As knowledge and standards circulated across world borders, the United Stated and the United Kingdom were quickly joined by other governments, including France, in drafting and assessing early regulatory regimes. This case also reveals the national particularities of safety management, including reactions to notable accidents including Three Mile Island in 1979, which led to divergences—sometimes large ones—in various country's national positions on the future of nuclear energy.

On the hypothetical

The promoters of nuclear energy, by the 1970s, had tried to spread a rhetorical change: they did not speak of nuclear accidents as impossible but "hypothetical." To this day, engineers and experts use the term "hypothetical accident" as they consider eventualities that are not *supposed* to occur—the reactors were designed to prevent accidents—yet certainly *could* occur. "Hypotheticality" was theorised in 1974 by West-German nuclear physicist Wolf Häfele, who participated in and led nuclear energy programs in the Federal Republic of Germany.[5] In designating the particularity of nuclear risk, Häfele theorised:

> Subdividing the problem can lead only to an approximation to ultimate safety. The risk can be made smaller than any small but predetermined number which is larger than zero. The remaining "residual risk" opens the door into the domain of "hypotheticality." …The strange and often unreal features of that debate, in my judgement, are connected with the "hypotheticality" of the domain below the level of the residual risk.
>
> (Häfele, 1974: 314)

Clearly, Häfele had enormous confidence about the improbability of a nuclear accident yet remained aware of the destructive potential. Experts could not totally exclude the possibility of a nuclear disaster but hoped to demonstrate that it was sufficiently unlikely in order to gain social acceptance. Häfele had provided, with the notion of "hypotheticality," a way to downplay risk and allay fear so that the nuclear industry might flourish.

But how can experts actually consider nuclear accidents hypothetical? The low number of large, severe accidents does not allow nuclear experts to assess nuclear safety only through first-hand experience. They develop a large range of concepts and tools to assess nuclear safety and to demonstrate that accident probability is low enough to be considered near impossible. I propose a retracing of the technical and social work needed to allow engineers, relying on a combination of technical features, representations, confidence and expertise, to render the accident "hypothetical." I also explore the material and institutional infrastructures implemented to deal with the risk of accidents as citizens, countries and anti-nuclear movements increasingly considered any nuclear danger socially unacceptable. I argue that nuclear experts and engineers framed the "accident" to inspire trust in efficient prevention. Despite uncertainty, nuclear energy's champions downplayed possible damage as hypothetical.

Three early stages in the age of nuclear energy help disentangle this shift. The first section will thus cover the emergence of nuclear energy as an *engineering project*. The second corresponds to the *industrialisation* of nuclear energy, as big projects were met by growing public contestation worldwide. And the third stage opened when the unexpected core-meltdown at Three Mile Island, PA, on March 28, 1979 spurred a new urgency around the concurrent needs to consider the probability and impact of severe accidents and to save—indeed, expand—the industry in which they occurred.

Defining a safe design: technical challenge of the early atomic age

After WWII, nuclear safety organisations sprang up in the main nuclearised countries, mostly linked to military nuclear applications. In the United States, the Atomic Energy Act (McMahon Act) signed by President Harry S. Truman in 1946 created the AEC to continue research initiated during the war. Toward the development of future munitions as well as peaceful applications, the AEC set up a Reactor Safeguards Committee by 1947. The body, charged with evaluating nuclear safety and hazards, was merged with the Industrial Committee on Reactor Location Problems (created in 1950) after the 1954 (new) Atomic Energy Act, forming the Advisory Committee for Reactor Safeguards (ACRS). In France, the AEC's correlate, the Commissariat à l'énergie atomique (CEA), formed in 1945, dealt with safety problems within the "*sous-commission de sûreté des piles*" (sub-committee for reactor safety) following the model of the United States and United Kingdom. This CEA subcommittee was specifically assembled to advise the French government on best practices for avoiding nuclear accidents without hampering nuclear development (Foasso, 2007).

In the international sphere, matters of safety were particularly discussed with regard to the development of civilian nuclear energy. After the launch of Atoms for Peace, the nearly two-week long first international Geneva conference in 1955 explored the potential of such peaceful applications of nuclear energy. This event helped establish a shared vision of a technical (Del Sesto, 1993) and political (Krige, 2010) utopia marked by the swift development of peaceful nuclear applications. The atomic future was posed as being so bright as to justify the new risks it created. In Session 6.2, "Reactor Safety and Location of Power Reactors," the Geneva Conference assessed the possibility, in terms of probability and consequences, of a nuclear accident. The American delegation concluded:

> We believe that useful electric power in large quantities can be generated by nuclear reactors. It is our concern that rapid progress shall be made but that enough caution be observed so that no catastrophic event will delay the fruition of reactor development.[6]

Their approach aimed to inspire confidence in reliable design, clearing a serious hurdle to the industrial development of nuclear power. The AEC had initially decided that nuclear reactors (particularly those dedicated to research and development uses) be located only in uninhabited areas for safety (Mazuzan and Walker, 1985) but, as the attendees in Geneva pointed out time and again, nuclear reactors would need to be sited close enough to large cities to provide electricity.[7]

At this point, the problem of safety—like the promise of limitless cheap energy—was expressed in economic terms. What could constitute an adequately safe design that would control the risk of accident, drastically reduce costs so that the effort of atomic energy was both profitable and competitive (understanding that profits would be affected by transportation costs should reactors be too remote), and realise the hoped-for atomic future? General Electric representatives in Geneva reported:

> To achieve the economic advantage of locating nuclear power reactors close to large communities, it is essential that the potential environmental radiation hazards be unequivocally eliminated. At the present time, it seems certain that inherently safe reactors can be constructed. Even if there is still a minute possibility of serious reactor accident, release of radioactive material to the environs can be prevented by a protective envelope, of which a large steel sphere is one feasible form.[8]

That is, as promoters promised a low probability of accident, they also began planning for and communicating the assurance of efficient containment of potential releases.

The issue of location is rooted in the specific American regulation of nuclear applications and the development of AEC accountability in the 1950s. To control the risk of accidents in civilian facilities, the AEC Reactor Safeguards Committee (later, the ACRS) decided in 1950 to pursue the isolation policy set for the WWII-era Manhattan Project. The committee stated, "It is unfortunate that our experience in the operation of nuclear reactors to date is small and the hazards to human life which may result from accident or faulty operation are believed to be great."[9] The authors noted, by way of example, how the early development of motor vehicles disrupted various aspects of life in New York City, and they proposed a very restrictive policy nicknamed the "rule of thumb." It required the establishment of an "exclusion distance," assessed through modeling a huge release of radioactivity from an uncontained reactor.

The exclusion radius was calculated with the formula "$R = 0.01 \sqrt{P}$," in which P is the reactor's full power (Okrent, 1978: 2–8). But in the mid-1950s, the ACRS sidestepped these regulations to allow the installation of light water reactors at Shippingport and Indian Point, sites too close to populated areas to comply with the American "rule of thumb." The ACRS concluded that these facilities' specific designs ensured the efficient containment of radionuclides in the event of an accident. As projects were examined on a case-by-case basis, the ACRS rejected the implementation of small reactors proposed for the perimeters of mid-size cities using no formal criteria but the experts' judgment (Okrent, 1981).

Later in the decade, AEC regulation staff began working on formal site criteria under the leadership of Dr. Clifford Beck. Guidelines released in 1961 more specifically determined that the exclusion area for a nuclear energy project must be calculated by considering a maximum acceptable human exposure of "doses of 25 rem whole body and 300 rem to the thyroid" (Okrent, 1978: 2–2) should an accident occur. This hypothetical accident, called the Maximum Credible Accident, was now a primary "focus of siting evaluation." (Okrent, 1978: 2–2) Designers now had to prove to the ACRS that the Maximum Credible Accident occurrence for any given facility would have no catastrophic consequences on the population or the environment and that any accident of lower intensity must be contained in this "envelope" (to further minimise consequences). This set of regulations was called "10 CFR PART 100."

Obviously, this calculation involved a fundamental problem: how to determine what constitutes the Maximum Credible Accident (MCA). University of California in Los Angeles (UCLA) physicist David Okrent, an ACRS member, explained that the notion of "credibility" was assessed by considering the number of potential *simultaneous* failures:

> In general, accidents would be considered credible if their occurrence might be caused by one single equipment failure or operational error, though clearly some consideration must be given to the likelihood of this failure or error. It has been suggested that this criterion might be extended to the assignment of decreasing probabilities to accidents which would be occasioned only by 2, 3 or more independent and simultaneous errors or malfunctions, with the possibility that accidents requiring more than 3 or 4 such independent faults would be considered incredible.
>
> (Okrent 1978: 2–1)

This distinction between credible and incredible, although well-discussed by experts, allowed regulators to sort out possible accidents, paying more attention to the most likely and ignoring the most improbable. Like all typologies, this would have irreversible material consequences—in this case, on the siting and design of nuclear reactors.[10] Even for its authors, the concept of an MCA remained admittedly imperfect. In presenting this new approach at the nuclear congress in Rome in June 1959, Dr. Beck argued,

> it is inherently impossible to give an objective definition or specification for 'credible accidents' and thus the attempt to identify these for a given reactor entails some sense of futility and frustration and, further, it is never entirely assured that all potential accidents have been examined. (quoted in Okrent, 1978: 2–31)

However, the "Maximum Credible Accident" became the ground basis of the licensing process. It took the name of "design-basis accident" and the designers needed to take them into account in the reactor's design. The "design-basis accident," if it occurs, must not lead to significant consequences thanks to adequate safety features.

In 1957, the AEC published a study out of the Brookhaven National Laboratory in Long Island, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants." also known as WASH-740 report. It focused on the potential consequences of a major accident and enlightened legislative debate over the Price Anderson Act, which would determine the liability level of nuclear operators, as well as insurance and compensations for victims of nuclear accidents. In the words of French sociologist Sezin Topçu, this was a way to "organise the irresponsibility" (Topçu, 2014) and foster private investment. In 1960, the Paris convention adopted the same principle, greenlighting European development of the nuclear industry despite its potentially unknowable and immeasurable consequences (Daston, 2016; Kyrtsis and Rentetzi, 2021). This report included a section headed, "A Study of Possible Consequences if Certain Assumed Accidents, Theoretically Possible but Highly Improbable, Were to Occur in Large Nuclear Power Plants," in which experts again asserted: "The probability of occurrence of publicly hazardous accidents in nuclear power reactor plants is exceedingly low."[11]

Under this regulatory scheme, scientists first determined the worst possible accident that could occur at a given nuclear power plant, regardless of probability. That choice spurred a major change in the way nuclear accidents were conceived. To this point, experts had considered that the main risk was a reaction runaway event, called a *reactivity accident*. Now they added that a Loss Of Coolant Accident (LOCA) followed by a core meltdown was the one case in which a large quantity of radionuclides would be released, because the molten core could alter the containment materials.[12] Nevertheless, designers and regulators continued to consider containment the best approach to coping with a LOCA and largely left uncalculated the potential for a core meltdown to alter and amplify the spread of nuclear fallout.

At the same time, a severe nuclear fire that occurred at Windscale in the United Kingdom on October 10, 1957 led to major changes in the United Kingdom's Atomic Energy Agency (AEA). At the second Atoms for Peace Conference in 1958, the AEA put forward a formalised containment philosophy later known as the "method of barriers."[13] This system relies on three independent, nested barriers: fuel cladding, reactor core vessel, and containment building. Each should be able to contain and reduce radioactivity even in case of leakage (a core meltdown damaging the cladding or a fuel fire), using a Russian doll set-up.

The first period of nuclear development led to the implementation of various infrastructures meant to overcome the hypothetical nuclear disaster that threatened the commercial exploitation of atomic energy. The hypotheticality of a nuclear accident had been established on two assumptions: the probability was low enough to be acceptable and the consequences of any accident would, thanks to careful design, be "containable." However, the massive spread of nuclear energy in the mid-1960s and its mounting public contestation contributed to a reframing such that, in addition to technical arguments, risks to the public had to be taken into account.

Demonstrating that the accident is hypothetical to experts and public

In the mid-1960 and the 1970s, the technical precautions that experts considered efficient enough to master the risk of nuclear accidents and sufficient to convince nuclear technicians could no longer satisfy the fast-growing anti-nuclear contingent. According to historians George T. Mazuzan and Samuel J. Walker, the changes in US regulation policies throughout the 1960s aimed to enhance public confidence in the AEC and its regulatory process (Mazuzan and Walker, 1985: 373). Therefore, the AEC decided not to substantially change its policies in terms of licensing, but to develop new processes of requiring proof of safe design, notably via experiments.

In the early 1960s, Dr. Beck, a North Carolina State University nuclear physicist and AEC member, had, for instance, investigated the interaction between water and zirconium. In the mid-1960s, the AEC came around to the idea that safety should be empirically demonstrated in tests like these, rather than continue to rely exclusively on calculations. But the first "semi scale" experiments performed at Idaho Falls National Laboratory to prepare for the Loss of Flow Test (LOFT) program and the WASH-740 report update showed that the Zirconium-water chemical reaction might be highly exothermic and, should a temperature of 1205°C be exceeded, lead to a major, uncontainable core meltdown (Okrent, 1981).

A few years later, the construction of the LOFT testing station at Idaho National Engineering Laboratory (INEL) was completed. Its scientists were permitted to perform experiments on core degradation in the event of a meltdown. Preliminary tests indicated that the Emergency Core Cooling System (ECCS) was not as reliable as had been assumed. Designers and regulators proposed a new strategy: enhancing the reactor's ability to reduce the leakage of radioactive material in case of damage. Frank Reginald Farmer, head of the Safeguard division of the Authority Health and Safety Branch of the United Kingdom's AEA made the proposal at the 1967 IAEA symposium on Reactor Siting and Containment, saying:

> Mr. Hake suggested that containment is required to meet a situation when the control system fails. For this event, it is very difficult to decide the course of the accident, taking into account molten fuel metal/water reactions and associated shock forces. It is precisely for this event that the value of containment is in doubt. There are other alternatives to containment, which have a comparable combination of availability and effectiveness. In the United Kingdom, we have shown that suitably designed suppression ponds will reduce iodine in the steam-gas mixtures by a factor of 30-300, and the availability of a pond is very good.[14]

Clearly, there were limits to the "design-basis accident" (determined with the MCA) regulatory approach to ensuring safety, and uncertainties concerning containment strategy continued to stymie the expansion of the nuclear industry.

Nonetheless, the exportation of reactors helped the US disseminate the risks inherent to reactor design in that country. Like most capitalist nuclearised countries, France was an importer of these American reactors. In 1969, after a huge competition between the French CEA and the state-owned electricity company, the Ministry of Energy abandoned the CEA's proposed gas-graphite reactor and instead adopted a light water reactor design using American technology (Hecht, 1998). The French American company *Framatome* bought licensed technology for a Westinghouse pressurised water reactor to aid the fast development of nuclear energy, importing US safety regulations alongside the technology. However, by the end of 1972, the Ministry of Industry SCSIN decided to launch a commission led by the safety department of the CEA to determine general standards for nuclear safety in France. The CEA's *Départment de Sûreté Nucléaire* (DSN) proposed "principles to be studied for the definition of accidents," particularly "*beyond design*-basis accidents," (worser accidents than the MCA) to prepare possible new regulations and emergency plans. Industrialists, such as *Framatome's* subcontractor (Groupement Atomique Alsacienne Atlantique—GAAA), pushed back:

> The approach proposed in this worksheet does not seem to us to be the best because it seems to make an arbitrary separation between

> accidents taken into account for the design and *beyond design*-basis accidents. This arbitrariness has the disadvantage of always leaving open the list of accidents to be taken into account for design.[15]

In a subequent letter, *Framatome* added:

> We are opposed to taking into account beyond design basis accidents. The manufacturer must carry out an installation where safety is guaranteed on the basis of a coherent list of accidents, drawn up in agreement with the safety organisations, and for which the installation is designed and dimensioned. The rule of the game must be set at the start: the manufacturer must work within a precise framework. The so-called "beyond design basis" accidents might become accidents taken into account for design.[16]

During a February 28, 1975 meeting, an array of French manufacturers reaffirmed that "the study of beyond design basis accidents should not, in [our] opinion, influence the design."[17] Apparently, industrial interests wanted to rely as much as possible on American criteria and practices rather than any stronger French restrictions.

The CEA's *Département de Sûreté Nucléaire* (DSN) launched construction on the Phébus Research Reactor in Cadarache in order to obtain experimental data on accidental situations (LOCA, in particular). The government hoped to address uncertainties about the ECCS's efficiency, following the efforts of other countries.[18] From the outset, though, the Phébus Research Reactor's construction was doomed. The CEA was under too much pressure to cut costs, and a competing research reactor, CABRI, which would study power excursions for CEA-designed fast breeder reactors, was an important focal project.[19] To ensure industrial funding, the first program, Phébus LOCA, was a compromise between DSN and the industry meant to "convince" Électricité de France (EDF) that it was necessary to study core degradation phenomena *beyond design*-basis accidents.[20] Before the Three Mile Island accident, EDF refused to support research on fuel behavior in beyond-design conditions, so the Phébus LOCA program studied fuel and zirconium cladding behavior, within design limits, at 1205°C (not coincidentally, the value determined by the US Nuclear Regulatory Commission [NRC]) to verify the validity of reference temperature without studying fuel behavior in a *beyond design*-basis situation.

At the same time, public communication was based on probabilities estimated by experts without using experimental data. Safety assessments based on the experts' judgment of "probability" were highly contested by independent experts from anti-nuclear organisations including the Union of Concerned Scientists (founded by Massachusetts Institute of Technology scientists in 1969). In 1972, facing criticism, the

AEC commissioned an ambitious study to assess the risk of a severe accident and its potential consequences in the United States from Professor Norman Carl Rasmussen, an MIT nuclear physicist. A team of 50 high-level experts worked full time, under Professor Rasmussen's supervision, to provide a nuclear accident probability assessment that was more "realistic" than the WASH 740 report study, which dealt with extreme accidents regardless of probability. The team borrowed from business school research, adopting the "event trees method" to consider both the reliability of systems and the probability of failures (Keller and Modarres, 2005; Esselborn and Zachmann, 2020). The final Rasmussen Report, released in 1975, challenged the MCA approach and demonstrated that the likeliest scenarios leading to a core meltdown were those involving multiple failures—the ones considered *incredible* in the 1960s. The study also emphasised the role played by human factors in the level of risks and demonstrated that the risk of core meltdown was higher than experts had previously claimed.[21] The AEC estimated that the probability of a large release of fission products (affecting 100 or more people) was around 10^{-9}, per reactor year, which meant a 1 in 100 million chance that any given reactor might experience such an accident in any given year. Comparing nuclear risks to other industrial and natural risks, the report concluded that nuclear risk was by far the lowest, excepting the risk of meteorite strike.[22]

The Rasmussen Report's ostensible demonstration of nuclear safety was not without controversy. The Union of Concerned Scientists prepared a counter-report, the Kendall Report, which deemed the AEC executive summary partial and unfair (Rip, 1986). The Kendall Report alleged that the probability of ECCS failure, reported at 10^{-1} per reactor year in the Rasmussen Report (for a 1 in 10 chance of failure), was even higher, taking into account data from the first LOFT test on ECCS performed at Idaho Falls (Ford, 1986). The United States commissioned another official report, this time to reevaluate Rasmussen. The resulting Lewis Report critiqued and revoked the Rasmussen Report's executive summary in January 1979 (Okrent, 1981).

While West Germany also decided to establish its own probabilistic safety assessment, France never launched such studies. EDF retained the main conclusion that "Risks incurred by the public due to nuclear power plants are, by far, lower than risks of other kinds," favorably comparing nuclear risks with the risks of natural, technological, and daily life occurrences like car accidents and deeming them, thus, socially acceptable.[23] EDF pointed out that the probability of core meltdown was higher than in its previous studies (6.10^{-5} per reactor year in Rasmussen, versus 10^{-6} per reactor year in the studies performed by EDF). It also noted that core meltdown was more likely after a *small* break in the primary circuit (8.10^{-5} per reactor year) than after a *large* one (5.10^{-5} per reactor year). EDF assumed then, from a technical standpoint, its assessment of risk was both more realistic and more pessimistic about human-factor data. Accordingly, EDF concluded that the core meltdown probability (6.10^{-5}) was "extremely reasonable" given the existing margin and human-factor improvements that could be achieved in the expansion of nuclear power.[24]

This report, prepared by the Probability Safety Assessment Department, did not, however, reflect consensus among EDF members. Some even pointed out weaknesses in the safety evaluations published in the report. Still, the organisation concluded that the risk of major accident was low enough that structural modifications or important R&D programs in France should not be delayed over that potential.

When the unexpected accident happens: believing that major accidents are hypothetical

On March 28, 1979, at 4 am, a technical failure exacerbated by human error caused a core meltdown at Three Mile Island, PA. Nearly half the reactor core melted, shocking the nuclear industry worldwide. Not only was this a once "unthinkable" scenario, but it was also a resounding disqualification of existing precautionary measures and the MCA. Contrary to what was foreseeable when the reactor was designed, the Three Mile Island accident was the consequence of *multiple* failures.[25] For Charles Perrow, a sociologist of organisations and member of the Kemenny investigation commission, this accident came about, in part, because technical complexities rendered individual operators unable to master every step involved in operating a nuclear power plant. Perrow dubbed Three Mile Island a "normal accident" (Perrow, 1981; 1984) in that organisational characteristics lead to *normal accidents*. The nuclear industry was, to Perrow, a prime example in which a complex organisation experiences normal accidents, because the complexity of operating an entire power plant was beyond the understanding of any single individual, thereby compounding the possible errors leading to and in reaction to nuclear accidents.

In the United States, President Jimmy Carter responded to the Three Mile Island crisis by commissioning an investigation into its causes. The resulting Kemenny Commission Report recommended reinforcing effective control of the NRC over the nuclear industry and strengthening the complementary role of ACRS. Further, it advocated better training for nuclear operators and better management of maintenance operations in order to mitigate the possibility that another small failure should, in a domino effect, result in a serious, multifaceted accident like Three Mile Island. Emphasising that this accident's consequences for the public, given the low level of radioactivity leaked from the plant, had been limited (Walker, 2004), the Kemenny Commission's report concluded that "if the country wishes, for larger reasons, to confront the risks that are inherently associated with nuclear power, fundamental changes are necessary if those risks are to be kept within tolerable limits" (Walker, 2004: 210–211).

Weathering massive public attacks, the NRC decided to launch its own investigation commission, the "TMI 2 Lessons Learned Task Force." It would be chaired by Mitchell Rogovin and accompanied by a freeze on all nuclear development projects until its conclusions were published. Neither Congress nor the NRC set a formal moratorium on nuclear energy (Temples, 1982), but the NRC set a pause in the issuance of licenses—a *de facto* moratorium (Walker, 2004; Wellock, 2021). After the Three Mile Island accident, and despite efforts toward safety and the reassuring conclusions of both Congress and the NRC, Reactor 2 was not replaced. New NRC requirements were deemed too expensive and the tarnished image of nuclear power too controversial; a slump in electricity demand settled the issue. The NRC's director, who worked to reassure the public during the Three Mile Island crisis, announced that the cleanup would take less than four years, helping things return to normal. But because of the costs and complexity of the cleaning process, the reactor was *never* cleaned up and *never* restarted. The second reactor at Three Mile Island (Unit 1) was finally shut down in September 2019.

In contrast, in France, neither the government nor the CEA considered reducing or delaying the use of nuclear energy. The Three Mile Island incident was reported in French media, and authorities declared that French reactors and operators were different enough to rule out such an accident in France. The CEA and SCSIN nevertheless sent groups of experts to the United States to gather technical information. After examining the accident, the French advisory expert group (*Groupe Permanent*) concluded that this accident did not challenge French safety principles, though it drew attention to the human side of nuclear operation and crisis management.[26]

This view of the Three Mile Island accident was certainly debated at the highest level of the CEA, particularly within the direction committee. The military division said it "defeated the concept of a reference accident," while the CEA General Administrator assumed that the French nuclear "safety philosophy was not deficient."[27] The CEA minimised the consequences of the Three Mile Island incident and decided that no major change should be made to the French standards:

> The fundamental principles of safety, the principle of barriers and what the Americans call "defence in depth," are not being challenged. We knew that safety analysis will always be unable to predict everything, including human errors, and the ultimate backup measures are there to deal with unexpected situations. It is therefore necessary to maintain this global concept of safety.[28]

The French Academy of Sciences asserted that the major damage caused by the accident in Pennsylvania had been due to a failure in public communication: the "psychological" aspects of both operation and crisis were, the Academy believed, poorly managed by American authorities.[29] The design was excellent and a state-owned, centralised company like EDF was a major advantage to the French authorities in implementing the lessons learned from the accident going forward.

However, the political consequences of the Three Mile Island accident worried both the CEA and the French Ministry of Industry. An accident's *political* fallout could affect the entire nuclear industry. Thus, because it would impose a moratorium on the opening of new nuclear facilities, these two bodies criticised a proposal to create an international regulation body for the harmonisation of safety practices.[30] The head of CEA even publicly deplored the US and German delegations to the June 1979 G7 summit in Tokyo, which argued for more international nuclear regulation.[31] France's strong pro-nuclear position in this moment may be connected to the second oil crisis in 1979, which urged the further development of new European energy sources (Bonneuil and Fressoz, 2016). Nuclear promoters, particularly in France, managed to again demonstrate the improbability of another accident such as Three Mile Island by decoupling this abnormal situation from a disaster with long-term impacts. The accident, they insisted, actually revitalised the promises of nuclear energy by showing first that, even in a beyond-design accident, efficient containment could prevent total disaster, and second that this abnormal event had simply pointed out design and operations weaknesses that could be fixed. With this discursive twist, nuclear promoters chose to present the accident as an important contribution to enhancing the safety of nuclear technology.

Conclusion

Making the accident hypothetical was a specific way to control the risk of severe nuclear accidents—an impossibility according to normal accident theory. The risk that was initially considered exceptional, with the image of a nuclear bomb in the background, was reframed as "hypothetical" by promoters of *civilian* nuclear reactors who needed to boost the social acceptability of nuclear energy.

As I have shown in this chapter, three major strategies were employed. First, technological reliability was declared "inherently safe" given adequate design. This safe-by-design strategy was borrowed from chemical industries, which saw their first large accidents in the 1950s and 1960s. (Kletz, 1999; Boudia and Jas, 2014) It became a common way to claim control over risks in the United States (Boudia and Jas, 2013) in the 1970s. Second, the champions of nuclear industry determined the "acceptable" consequences of a potential accident on the basis of exposure norms (called radioprotection norms) developed by the International Commission on Radiological Protection (Boudia, 2008), even as others protested that there were no acceptable radiation risks. Third, to validate project designs, designers and experts adopted an approach based on the safety assessment of consequences on the assumed MCA of each facility.

The response to the exceptional nuclear risk is a combination of conventional practices meant to master the new risks and the contestation by extensively considering the likeliest accidents but leaving aside far riskier "hypothetical accidents." The risk has been technically controlled and decoupled from its inherent political dimension (Douglas and Wildavsky, 1983; Perrow, 1984; Beck, 1992). This technological approach is strongly linked to the risk assessment analysis performed by nuclear experts, without consulting the public or taking contestation into account. Because the public has been generally considered "ill-informed" and unable to take part in technological decisions, we can see that the management of nuclear accidents via preemptive regulation in design and siting actually exemplifies the deficit model characteristic of twentieth-century politics. Making the accident hypothetical means dealing with virtual accidents, which fosters confidence in preventive measures, despite the material consistency of nuclear risks.

Notes

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4 Atomic Energy Commission, "Summary Report of reactor Safeguard Committee," Technical Information division, ORE, Oak Ridge WASH-3, 1950, pp. 1–2.
5 I would like to give warm thanks to Stefan Esselborn of TUM München for this very useful reference.
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10 The material implication and consequences of classification has been extensively studied by Science and Technology Studies (see, for example, Bowker and Star, 1999; Busch, 2013).

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16 Lettre de réaction de Framatome aux Fiches du DSN, January 27, 1975, FAR 08, IRSN archives, Fontenay-aux-Roses, France Translated by the author.

17 Compte rendu de la réunion du groupe de travail Réglementation technique générale des réacteurs, February 28, 1975, p. 3, FAR 08, IRSN archives, Fontenay-aux-Roses, France Translated by the author.

18 Note Dg PSN 73-467 du délégué à la Mission Protection et Sûreté Nucléaires à Monsieur l'Administrateur Général, septembre 19, 1973, p. 1, FAR 08, IRSN archives, Fontenay-aux-Roses, France.

19 Note Dg PSN 73-467 du délégué à la Mission Protection et Sûreté Nucléaires à Monsieur l'Administrateur Général, septembre 19, 1973, p. 6, FAR 08, IRSN archives, Fontenay-aux-Roses, France.

20 Interview with a retired CEA-IPSN engineer, by the author.

21 EDF's first studies anticipated a general risk of core meltdown of approximately 10^{-6} per reactor year, while the Rasmussen Report assessed it at a level of 6.10^{-5} per reactor year (*Note Technique* SEPTEN E-SE/SN 74-36 (written by L. Prouteau); *Analyse du rapport Wash 1400 du Professeur Rasmussen sur la Sûreté des Réacteurs Nucléaires,* 7 novembre 1974, FAR 08, IRSN archives, Fontenay aux Roses, France.

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23 *Note Technique* SEPTEN E-SE/SN 74-36, Prouteau, *Analyse du rapport Wash-1400.*

24 *Note Technique* SEPTEN E-SE/SN 74-36, Prouteau, *Analyse du rapport Wash-1400.*

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30 Groupe CEA, Compte rendu du conseil de direction du 14 mai 1979.
31 Letter from the Directeur Général of the Direction générale de l'énergie et des matières premières of the Ministry of Industry, François de Wissocq, Lettre DGEMP/A N°290, May 7, 1979, FAR 08, IRSN archives, Fontenay-aux-Roses, France.

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