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# From Containing the Atom to Mitigating Residual Risk: The German Imaginary of Nuclear Emergency Preparedness

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**Abstract:** Grounded in a social scientific research approach, the present case study traces the shift in the German nuclear regulatory culture from prevention to preparedness, the latter of which builds upon decision support systems for nuclear emergency management. These systems integrate atmospheric dispersion models for tracing radioactive materials released accidentally from nuclear facilities. For atmospheric dispersion modelers and emergency managers, this article provides a critical historical perspective on the practical, epistemic, and organizational issues surrounding the use of decision support systems for nuclear emergency management. This perspective suggests that atmospheric dispersion models are embedded within an entire assemblage of institutions, technologies, and practices of preparedness, which are challenged by the uniqueness of each nuclear accident.

**Keywords:** decision support; nuclear emergency; preparedness; simulation; imaginaries

## 1. Introduction

In the history of nuclear technology, major shifts in national cultures of risk assessment and mitigation seem to align well with dramatic events. The German case, for example, reveals a pattern of positive assessment, preparedness, and pre-emption in the way in which nuclear risks have been addressed not only technically but also socio-politically. Rather than being inherent to the nuclear expert community, the transition from assessment to preparedness, occasioned by the Chernobyl accident from 1986; and from preparedness to pre-emption in the form of the nuclear phase-out decision, occasioned by the Fukushima accident from 2011, appear to have been the result of a series of cumulated tensions generated by sociotechnical and techno-natural disasters, revisions of mindsets, public opposition, and political action. Drawing on the concept of sociotechnical imaginaries [1], this paper aims to provide a theoretical underpinning to these subsequent shifts in the German nuclear risk issue. (The sociological concept of “imaginary” (or social imaginary) stands for the values, institutions, laws, and symbols that play a role in people’s imaginations of a social reality that is common to a social group or society. The more focused concept of “sociotechnical imaginary” is explained in Section 3) The key to understanding this evolution, I believe, is to focus on the technologies and practices used in Germany as a regime of nuclear disaster preparedness, which ensured the continued operation of nuclear power plants in that country after the Chernobyl accident. In the wake of the Fukushima accident, some scholars observed a shift from prevention to mitigation in the cases of Japan and the US [2,3]. By contrast, I would argue that Germany took this step almost two decades earlier. Therefore, in 2011, it reverted to pre-emptively phasing-out nuclear power on the basis that the effects of accidents are much greater than what the concept of residual risk conveys [4]. A belief in the possibility of mitigating residual risks, which represented the essence of preparedness and the rationale that kept the German nuclear industry “alive” between 1986 and 2011, suddenly disappeared. The Fukushima accident had shown that, even

in highly technologized democratic countries, the effects of residual risks are likely to surpass the “containment” power of any culture of emergency preparedness. On the theoretical side, this suggests that nuclear emergency preparedness is heterogeneous and dialectic and that it pertains to entire technological systems rather than isolated parts of them, such as expert communities and atmospheric dispersion models. On the practical side, the history of the German nuclear issue provides a complete, paradigmatic example of how, over time, technologies may reveal new faces and consequences of the risks they entail; and, as this example further suggests, it is only when the institutions, technologies, and practices of preparedness designed to mitigate those risks fail themselves that issues considered strictly technical by experts are solved through political action.

The paper is organized as follows: It begins with a review of the relevant social scientific literature on the Fukushima nuclear accident before introducing the theoretical framing and research design. Then, it traces the shift in German nuclear regulatory culture, from prevention to mitigation, back to 1986 and provides some insights into the technologies and practices of German nuclear emergency preparedness and the way in which they were used in Germany during the Fukushima accident. Then, it discusses how German emergency preparedness was challenged by the Fukushima experience, based on official reports on the accident from Germany and Japan. Finally, these issues are discussed in light of the German nuclear phase-out decision.

## 2. Fukushima Daiichi—A Challenge for Nuclear Preparedness

The Fukushima accident from March 2011 prompted divergent national energy policy responses. While, for example, Britain remained firmly committed to expanding its nuclear capacities [5], Germany returned to a previous political commitment from 1998 to phase out nuclear energy. The decision came only weeks after the onset of the accident and took the nuclear community by surprise, considering that, in December 2010, the same conservative-liberal government took a step towards the rescindment of the phase-out policy by extending the lifetime of several reactors [6]. Nuclear experts considered that their government ignored the reactor safety study (the Federal Office for Radiation Protection [7]) requested by the parliament immediately after the Japanese accident, in which they saw a confirmation of the safety of German nuclear plants. Instead, the government chose to follow the recommendation by a government-appointed ‘Ethics Commission’ to phase out nuclear power within 10 years on the basis that the severity and uncontrollability of an eventual accident on German ground should be considered in the assessment of residual risk [6]. As Hermwille [8] notes, the narrative of nuclear power as an uncontrollable threat outperformed that of nuclear power as a bridging technology in the Ethics Commission’s recommendation. Some analysts of the German nuclear phase-out decision consider that its main purpose was to pre-empt a victory of the traditionally anti-nuclear “Green” party in the then upcoming federal elections [5,9]. Other scholars contend that the accident only provided a system of elites, which failed to leverage a risky yet promising technology, with a policy window and thus an opportunity to get out of the nuclear issue in a somewhat honorable way [10,11].

Writing about the Three Mile Island (TMI) accident, Perrow [12] argues that, in large tightly coupled and highly complex technical systems, accidents are “normal” and will likely occur with a certain regularity. For the evacuees, cleanup workers, and crisis managers of the Fukushima accident, however, the experience was likely anything but normal. On the energy policy level, in Germany, Switzerland, and Belgium, the accident opened a policy window to accelerate the phase out of nuclear power, although it happened thousands of miles away from these countries. Whereas experts considered that the accident was triggered by a series of “beyond design basis” causes and failures [13], for others, Fukushima was a techno-natural disaster [14], a compound disaster [15] the triple disaster from “3/11” [3], an ‘envirotechnical’ disaster [16], or one of the most important events of the 21st century [9]. “Being post-Fukushima” requires a more intense preoccupation with sociotechnical risks rather than strictly technical ones, Kinsella [3] notes. Confronting the commonly held belief that Fukushima was primarily caused by political interference with technology, Pfothenauer et al. [17] argue

that “political values and interests are continually part of nuclear operation” (p. 79). Prichard [16] also notes that environmental interferences with the politics of the nuclear have created ways of eluding responsibility for the accident as “government regulators and industry officials have conveniently pointed to the earthquake and tsunami in an attempt to absolve themselves of responsibility” (p. 224).

On one reading of Pfotenhauer et al. [17], the modeling of a complex sociotechnical system would actually entail building a model of the world itself, as it “incorporates sociotechnical assumptions that modelers and decisionmakers need to keep in mind” (p. 82). Modelers and decision makers might then simply regard the Fukushima evacuations and cleanup works as a real-world experiment, which entailed the reordering of space and a redistribution of agency and a reconfiguration of power relations, as Felt [18] notes. Farmlands and villages were redefined as irradiated zones and “people were reconceptualized as ‘at-risk-subjects’ expected to behave in specific ways” (p. 8). Complementing Felt’s reflection, Gabrielle Hecht provides a compelling account of the cleanup practices of the Japanese nuclear industry by focusing on whom she calls “nuclear janitors” [19]. These blue-collar workers, employed by a chain of subcontractors, perform cleanup works after accidents as well as regular maintenance works at nuclear power plants (NPPs) under extreme conditions and exposure to high levels of radioactivity. Drawing on Perrow’s concept of “eco-system accidents,” which reflects the tight coupling of human-made and natural systems between which “there are few or no deliberate buffers because the designers never expected them to be connected” (p. 222), Pritchard [16] regards Fukushima as an “envirotechnical disaster” in which the air, the water, and the bodies of “nuclear janitors” became part of a hybrid envirotechnical system—the reactor—requiring constant attention because it can never be completely shut off. This explicit and unprecedented entanglement between humans, technology, and nature perhaps explains why the media “forgot” about the greater disaster caused by the tsunami and chose to focus on the coverage of the “fascinating” nuclear accident at Fukushima instead [20,21].

Felt [18] notes that, through the use of radiation maps, the location of a person became analogous to the risk of exposure to radioactivity, which turned living space and peoples’ homes into evacuation and health hazard zones. Radiation maps caused an ontological redefinition of space—from one of living, leisure, and agricultural productivity to a risk zone. Perhaps for these reasons official radiation maps published by the Japanese authorities were challenged by participatory “do it yourself” maps generated using personal Geiger counters and publicly available technologies of preparedness [22,23]. Radioactivity maps are central technical artifacts used to prepare for and manage nuclear emergencies. They are visually compelling, color-coded, geospatially bound representations of radiological risk and have been the subject of controversies during the Fukushima accident [22]. Kera et al. [23] and Plantin [22] analyzed the ways in which online maps facilitated a certain mode of participation in assessing the radiological situation after the Fukushima disaster and thus confronted the official radiation maps, while pointing to the implications for risk governance and disaster management.

“Disasters prompt us to seek lessons” [17], but what kind of lessons can be learned from a “beyond design basis” accident? Kinsella notes that, “[i]f Fukushima was beyond its engineering design basis, it was also beyond the ‘limits of representation’ for a sociotechnical system that has exceeded its creators’ vision of control” [20]. Wittneben [5] also notes that, for Germans, Fukushima was beyond the ‘largest conceivable accident’ (GAU), labeling it as a “Super-GAU”. In this context, Schmid [2] notes that the Fukushima accident “prompted a shift from a ‘zero risk mindset’ to one that emphasized preparedness for a nuclear emergency” (p. 199). While in hindsight preparedness is almost never considered sufficient [2], some experts still argue that it should be based on detailed planning and past experiences [24]. Schmid [2,25] also argues that nuclear emergency response should leave room for improvisation rather than focusing on control and regulation alone and that it should consider the specificities of local and national technological and regulatory cultures in an integrative way in order to enable an orchestrated international emergency response team.

These contributions to the literature on the Fukushima accident reflect a strong interest in what happened around rather than inside the damaged reactors at Fukushima during the nuclear crisis from 2011. This paper contributes to this body of literature from another geographical perspective,

by analyzing the German technologies and practices of nuclear preparedness. As I shall argue, the shift from a 'zero risk mindset' to one that emphasizes preparedness for nuclear emergencies observed by Schmid [2] in the Japanese case occurred in Germany some 25 years earlier. By exposing the limits of preparedness in its currently imagined form, the Fukushima experience prompted another shift in the German regulatory culture toward pre-emptively phasing out nuclear power by 2022.

### 3. Theoretical Framing: Sociotechnical Imaginaries

Differentiating them from master narratives and media packages, Jasanoff and Kim [1] define sociotechnical imaginaries as "collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific and/or technological projects" (p. 120), which are "associated with active exercises of state power, such as the selection of development priorities, the allocation of funds, the investment in material infrastructures, and the acceptance or suppression of political dissent" (p. 123). Imaginaries articulate feasible futures while also warning against innovation risks and hazards. Felt [26] developed this conceptual framework further by showing that imaginaries need not necessarily promote technologies but also resistance against them; and that they undergo a process of stabilization through rehearsal. Jasanoff and Kim [27] note that sociotechnical imaginaries play an important role in defining national energy policies and several scholars have followed this lead. Tidwell and Smith [28], for example, describe the energy security imaginary in the USA by tracing the genealogy of energy policies in that country. Eaton et al. [29] analyze how the US national imaginaries of bioenergy development are interpreted differently by local and nonlocal actors, while observing that competition exists between different imaginaries at a given time. Levidow and Papaioannou [30] also discuss three competing imaginaries of bioenergy innovation envisioned by the UK government. Tidwell and Tidwell [31] note that sociotechnical imaginaries provide a compelling theoretical framework for documenting how "techno-epistemic networks" construct notions of society while producing knowledge for technology policy and design in the energy sector.

To elaborate the sociotechnical imaginaries concept, Jasanoff and Kim [1] used the example of the post-WWII nuclear history in the USA and Korea. According to these authors, an extensive program aimed at "containing the atom" was started in these countries after the famous "Atoms for Peace" discourse of then US president Dwight D. Eisenhower before the United Nations' General Assembly in 1953. As Jasanoff and Kim [1] note, this discourse signaled an attempt to "reimagine the atom in a self-contained new ontological frame, that of peace rather than war, and of sustaining life rather than destroying it" (p. 126). In this sense, the idea of containment was aimed at different "energies." One of them was the image of the US as a superpower, which emerged after WWII. Another one was the fear of the clash between the two atomic superpowers of that time—the US and the Soviet Union. As Jasanoff and Kim [1] note, "[t]hese embryonic exercises in public reassurance (the taming of fear) continued after the war, as the state attempted to harness, tame, and commercialize the energy of the atomic age" (p. 128). To convince the public that the threat of radioactive releases can be effectively contained, policymakers in the US stressed that unmanageable releases are not possible. As these authors further note, policymakers were backed by the law and the courts that ruled in favor of the nuclear industry whenever public resistance emerged against nuclear projects in the US. In this sense, the law produced what Jasanoff and Kim call "procedural containment" where experts and politics did not manage to block the uncertainties linked to the threat radioactive releases. By the example of "the atom", Jasanoff and Kim [1] thus illustrate how sociotechnical imaginaries help to frame urgent risks, define the main focus of policy, articulate controversies, and provide the means and avenues for closure by appealing to "culturally specific ways in which publics expect the state's expertise, knowledge, and reasoning to be produced, tested, and put to use in decision making" [32].

Building on this theoretical framing, the current paper aims to trace the emergence and stabilization of a culturally sensible German imaginary of nuclear emergency preparedness out of the established imaginary of containment. This process was partly determined by the strong German anti-nuclear movement grounded in a tradition of pervasive risk-consciousness and risk aversion [27],

the radiological effects of the Chernobyl accident, and the specific reaction of the German polity and society to these “post-containment” circumstances.

#### 4. Research Design

The research sought to find out what kind of post-containment sociotechnical imaginary emerged and stabilized in Germany after the Chernobyl accident by looking into how computer simulation-based systems became important residual risk mitigation tools in that country and investigating how different regimes of preparedness were affected by the Fukushima accident. Empirically, the study draws on regulatory guidelines, scientific papers, and official reports on the Fukushima accident as well as the author’s personal experience as a member of the scientific staff of the Institute of Nuclear Technology and Energy Systems (IKE) in Stuttgart between 2007 and 2012. In addition, participant observations in the form of field notes of IKE’s public activities during the Fukushima accident and two interviews with IKE experts were used. In the late 1980s, the Institute of Nuclear Technology and Energy Systems started developing an atmospheric dispersion forecasting and dose projection system, called ABR-KFÜ. This system was used at the regional level by the state government of Baden-Württemberg for the purpose of providing simulation-based support to nuclear emergency managers until 2017, when it was replaced by another system, which is now used at the federal level. Following Jasanoff’s [33] methodological suggestions, the analysis of regulatory guidelines and policies as well as that of relevant scientific papers was drawn upon to facilitate a better understanding of the German nuclear regulatory culture and the role of different technologies of preparedness within it. In addition, the analysis of official reports on the Fukushima accident helped to identify expectations of nuclear emergency preparedness in the wake of the latest severe accident.

A grounded theory approach [34] helped to identify and describe the main characteristics of the imaginary of preparedness based on data consisting of documents, participant observation notes, and interview transcripts. Strauss and Corbin [34] define grounded theory as “theory that was derived from data, systematically gathered and analysed through the research process. In this method, data collection, analysis and eventual theory stand in close relationship to one another,” whereby the researcher “begins with an area of study and allows the theory to emerge from the data” (p. 12). The approach thus aims to create the basis for a new theory by analyzing the concepts and categories resulting from an extended and interrelated process of collecting, analyzing, and coding qualitative data. Within the grounded theory approach, coding is the method by which field notes, interview transcripts, and other artefacts (e.g., regulatory guidelines) are reviewed, whereby recurring themes within the social worlds of the individuals being studied and aspects of potential theoretical importance are emphasized and labeled in the data. At the same time, the data are continuously compared with existing theoretical concepts and categories until a theory that best explains the identified recurrent themes is found. In a further step, the researcher attempts to link together the identified categories around a central category to the end of articulating a theoretical model explaining the phenomenon being studied.

In a first step, I investigated the history and rhetoric of the inherently safe reactor concept, which seemed to reflect a reinforced imaginary of containment. This preliminary analysis suggested that the sensitizing concept of sociotechnical imaginaries could also be used to capture the spirit of nuclear emergency preparedness. Then, I selected relevant documents for the analysis and conducted interviews with IKE experts to fill the gaps in the publicly available documentary sources. The emphasis fell on the development and use of decision-support systems for nuclear emergency management before and during the Fukushima accident. In a third step, starting from the observation that an imaginary of preparedness was at work, I focused on identifying its key features by reviewing the practices and concerns of nuclear emergency managers in that country. Considering the history of the German nuclear issue, my observations suggested that these practices and concerns were indicative of a culture of preparedness, which emerged after the Chernobyl accident and emphasized mitigation rather than prevention.

In the following sections, the key results of this analysis are presented and discussed.

## 5. From Containing the Atom to Mitigating Residual Risk

The Three Mile Island (TMI) accident of 1979—the first event of its kind to evoke widespread media exposure [35]—attracted public attention to the residual risks of nuclear power production. Residual risks are hazards that are unknown or have a very low likelihood of becoming a threat and therefore are not accounted for in the design of reactor safety systems. In response, two main paradigms crystallized during the 1980s. The first one sought to develop new technical means for ensuring inherent safety by guaranteeing the containment of radioactive materials within the reactor or the nuclear fuel elements under all circumstances. To this end, shortly after the TMI accident, the idea of a “forgiving reactor” [36] able to tolerate the errors of its operators was brought forward within the nuclear community. Weinberg and Spiewak [37] defined it as a reactor “whose safety depends not on the intervention of humans or of electromechanical devices but instead depends on immutable and well understood laws of physics and chemistry” (p. 1399). To present their concept as a *sine qua non* condition for the survival of the nuclear industry, Weinberg and Spiewak perhaps unknowingly used Perrow’s [12] argument regarding the “normality” of nuclear accidents: “At present, with about 500 large reactors (operating or under construction) in the world, a core melt probability of  $10^{-4}$  per reactor year implies an average accident frequency of one every 20 years” (p. 1401). This acknowledgement of the vulnerability of reactor operation reflects a symbolic breakaway of part of the nuclear community from the then established practices of nuclear risk assessment, which allowed for so-called “subjective probabilities” based on expert judgement as an acceptable compensation for the lack of extensive experimental data on the actual safety of any given reactor design [38]. As Miller [38] notes, within the discourse of risk assessment, subjective probabilities represented a conversion of ethos into logos whenever the quantification of risks based on data was not possible. The *forgiving* reactor would fix this vulnerability by ensuring an inherently safe system by design. With the first inherent reactor safety concepts dating back to the 1950s [10], the proponents of the *forgiving* reactor seized a moment of opportunity in the history of nuclear technology to revive a concept, which seems to make a comeback every few decades ever since [39–41].

The metaphor of a *forgiving* reactor—an anthropomorphism of the technical term *fault-tolerant* reactor—invites us to imagine a system able to tolerate the mistakes or ‘sins’ of its operators by creating a link between a technical system property and a profoundly significant cultural value. As Edwards [42] notes,

“[metaphor] . . . is far more than a rhetorical device. It mediates the relationships among language, thought, and experience. [ . . . ] A metaphor channels thought and creates a coherent scheme of significance not only by making certain features central, but by establishing a set of connections with other metaphors and openings toward further elaboration. This means that metaphor is not merely descriptive, but also prescriptive (p. 157).”

In its prescriptive function, the metaphor of fault tolerance as forgiveness arguably hoped to resonate beyond the boundaries of the nuclear community. To restore the social and political consensus on the future of nuclear power it seemed to appeal to a wider public’s willingness to forgive nuclear experts for the “mishap” at Three Mile Island just as the inherently safe reactor would forgive the mistakes of its operators. However, due to the high costs and economic risks involved with changing paradigms in a profitable industry, the forgiving reactor met resistance from within the nuclear community. By the end of the 1980s, inherently safe reactor prototypes were gradually abandoned also because of various flaws in the design of the fuel elements, which were key to the success of the concept. In Germany, the most advanced experimental inherently safe reactor called AVR was shut down in 1988 by the regulatory authorities due to a series of safety-related reactor incidents [43] caused, among other things, by friction between the spherical graphite fuel elements, called pebbles.

The attempt to export the related Pebble Bed Modular Reactor to South Africa also failed because of financial difficulties [44].

Although the risks associated with operating NPPs were proven real by the TMI and the Chernobyl accidents, the technology was considered a necessary compromise for bridging the decades until the fusion reactor or some other technology would replace it. This is perhaps why the second paradigm prevailed in Germany; it counted on continuously improving the active safety systems of the conventional and profitable light water reactors and on mitigating the effects of realized residual risks by monitoring the radioactive emissions around them. This facilitated the development of simulation-based decision-support systems for nuclear emergency management, which became essential residual risk mitigation technologies after 1986. The culturally entrenched practice of continuously improving technical systems attracted most German nuclear experts, who acknowledged the possibility of future accidents and the need to address residual risks through mitigation technologies. The paradigm thus shifted from containing a physical force to mitigating the second order risks of nuclear technology, which provided more levers for risk managers. Mitigation technologies can be specially tailored for each type of risk and aided by countermeasures and carefully planned emergency responses outside the boundaries of NPPs. The notion of risk thus became the epistemic focus in dealing with reactor safety and nuclear accidents in the post-Chernobyl period. This shift is perhaps best reflected in Ulrich Beck's concept of a *risk society* [45], which he developed around that time.

Growing out of the challenged imaginary of containment, the paradigm of nuclear emergency preparedness may be regarded as a second-generation sociotechnical imaginary, which acknowledges the residual risks of nuclear power plant (NPP) operation, yet still manages to articulate a feasible future in which these risks can be effectively mitigated through specially tailored *technologies of mitigation*. Similarly to the imaginary of containment, endorsed by the Price Anderson Act [1] in the USA and by the Atomic Energy Act from 1960 in Germany [27], the imaginary of preparedness was stimulated by the German Precautionary Radiation Protection (PRP) Act (Strahlenschutzvorsorgegesetz (StrVG), 19.12.1986, BGBl. I S. 2610.) passed in December 1986 to the end of facilitating an effective coordinated emergency response to nuclear accidents. In a sense, the PRP Act patched the imagination that radioactivity and fear can be effectively contained by adding a layer of preparedness to it. As Jasanoff and Kim [27] note, "Germany displays a postwar history of pervasive risk-consciousness and risk aversion" and a political tradition in which "the state is responsible for assuring the safety and security of its citizens" (p. 192). In this sense,

"[u]ncertainty emerges as perhaps the gravest risk in the German imagination . . . [and] political energy accordingly focuses principally on the (re)creation of predictability and order at moments of significant technological change, with law as the instrument for clearly allocating responsibility, and with expertise, largely uncontested, as the law's indispensable ally in controlling epistemic ambiguity" (p. 192).

By aligning the allowable radiation levels with the more permissive international standards, the PRP act ensured the continued operation of NPPs in spite of the long-term radiological effects of the Chernobyl accident [46]. The law also tackled the perceived uncertainty concerning the risks of radiation by establishing the "effective dose model" as the official scientific method for assessing radiation exposure, which encouraged the development of different simulation-based tools and practices of preparedness as a public safety net in the face of possible future accidents. As Günter and Dietz note, whereas before Chernobyl the nuclear complex tried to exclude the potential hazards of nuclear facilities by reverting to terms such as residual risks, the new law created an operational framework for controlling and managing the effects of a now reasonably conceivable "maximum credible accident" caused by the realization of such risks. This residual risk mitigation principle became the substance of preparedness in the post-Chernobyl nuclear era, which facilitated a return to state-assured nuclear safety and security for its citizens through the "(re)creation of predictability and order" in line with the German political tradition.

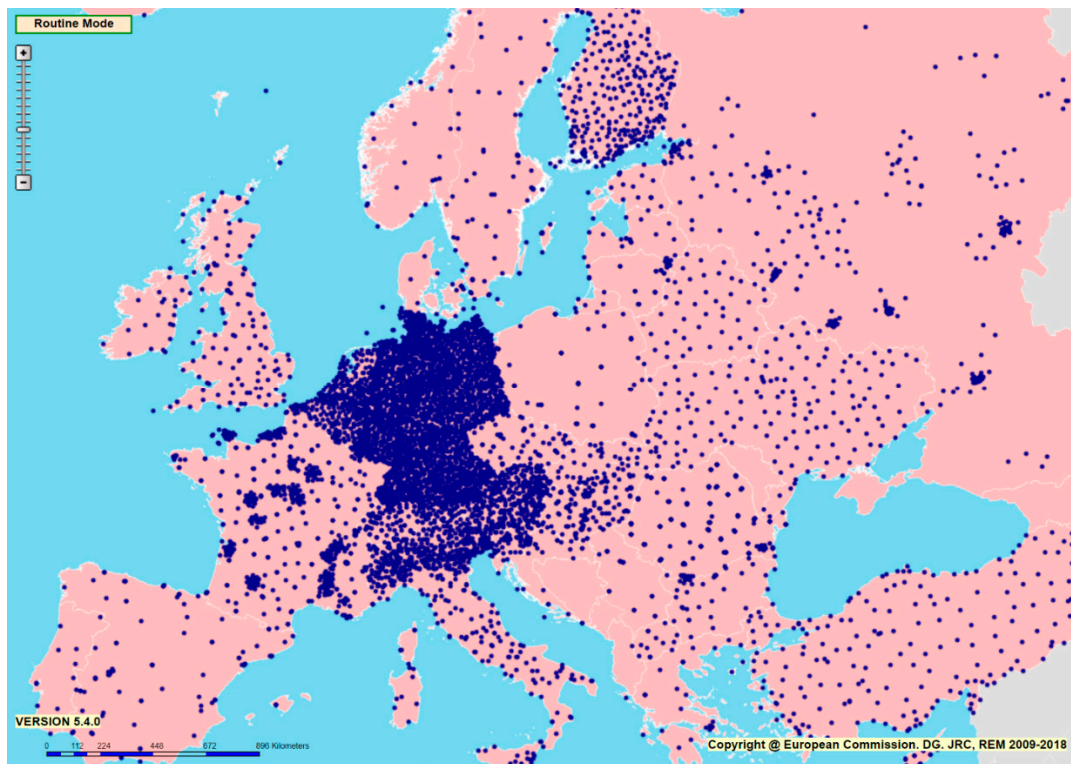
### 5.1. Technologies of Preparedness

In response to a reactor incident from 1977 at the Gundremmingen nuclear plant, the first system for remotely monitoring nuclear reactors was introduced in Bavaria in 1978 [47]. Similar systems were introduced in the following years by other federal states. These early monitoring systems consisted of a few dozen radioactivity monitoring stations installed around nuclear plants which provided regulators with data through a modem line. The PRP Act laid the ground for the development of a nation-wide monitoring system called Integrated Radioactivity Information and Decision Support System (IMIS) [48], which relies on a dense network of radioactivity measurement stations. In addition, the Federal Office for Radiation Protection (BfS) was founded with the mission to coordinate nationwide radioactivity measurements, atmospheric dispersion forecasts, and dose estimations. In the wake of the accident, energy producers could continue operating NPPs, provided they contributed to the development and maintenance of the IMIS system and cooperated with regulators on a regular basis.

The IMIS system continuously monitors environmental radioactivity to detect even slight changes and long-term trends [49]. While providing the world's perhaps densest national network of high-quality radioactivity measuring stations, IMIS is primarily considered an instrument of emergency preparedness, which aims to create the appropriate bases for decisions about protective countermeasures in case of serious incidents and accidents. The INIS system is also emblematic for the shift in the country's nuclear regulatory culture, from risk prevention to mitigation, caused by the nuclear controversy, different incidents at German nuclear plants, and the radiological effects of the Chernobyl accident. Compared to other countries, the density of the INIS network (Figure 1) is symbolic of the Germans' wary relationship with radioactivity and its man-made sources, seconded by Austria—a German speaking nuclear-free country, which pre-emptively shut down its only NPP by referendum [50]. The EURDEP map may be regarded as a cultural map, showing that, along with Germany and Austria, Belgium and Switzerland also seem very concerned about radiological risk. Indeed, after the Fukushima accident, Belgium and Switzerland were the only two countries to also announce plans to phase out nuclear power.

An important extension to the system consisted of computer-based models for immediate decision support in nuclear emergencies. These models use emission data from the IMIS network and meteorological data from the German Weather Service to produce comprehensive small-to-mid-range atmospheric dispersion and dose forecasts (or projections). Given the relatively small range of the models and in consideration of the principles of federalism, the environment ministries of each federal state were left in charge of contracting, operating, and supervising the development of decision-support systems based on atmospheric dispersion models. Consequently, local cultures of preparedness are also embedded in these systems. In 1989, the first version of the "ABR-KFÜ" decision-support system for nuclear emergency management [51] developed by the IKE in cooperation with private companies was introduced in Baden-Württemberg. Being very innovative for that time, it reached the international spotlight (Figure 2). Using simulation models, which were updated regularly to match the state of the art, the system promised to deliver the necessary support in case of a real emergency. Following its initial success, the system received considerable funding and attention from the Ministry of the Environment and the nuclear industry. Beck [45] notes that one of the features of risk society is that new technologies are used to mitigate the risks entailed by existing technologies. In this sense, the ABR-KFÜ system can be regarded a technology for mitigating what Beck called "second order risks"—that is, risks generated by man-made technologies rather than nature.





**Figure 1.** EURDEP map of European radioactivity monitoring stations. Source: <http://eurdepweb.jrc.ec.europa.eu/EurdepMap/Default.aspx> (Accessed on: 20 July 2018).



**Figure 2.** 1989—Institute of Nuclear Technology and Energy Systems (IKE) experts show Mikhail Gorbachev (then president of the UDSSR) a simulation of the atmospheric dispersion of radioactive materials from the Chernobyl accident site produced by the ABR-KFÜ system (Courtesy of Dr. Walter Scheuermann).

In contrast to the purely linguistic metaphor of the forgiving reactor, the German imaginary of preparedness was construed around the visual metaphor of radiation maps. These maps provide visualizations of an imminent risk of radiation exposure, while conveying the impression that the

affected areas can be evacuated in the attempt to mitigate that risk. To gain legitimacy and acceptance as mitigation technologies, radiation maps needed to prove themselves effective *ante factum* by providing the support for an entire assemblage of technologies, practices, protocols, and policies of nuclear emergency preparedness anchored in local cultures of political responsibility and accountability.

In the following, a description of the key elements of this assemblage is provided.

### 5.2. Structure and Responsibilities of the Nuclear Emergency Task Force in Baden-Württemberg

The content of this section is based on an interview with a permanent expert advisor and member of the nuclear emergency task force. As stipulated by the PRP Act, in Germany, the individual state governments oversee the immediate countermeasures in nuclear emergencies for a limited area (currently 200 km) around the accident site. Afterwards, the federal government takes over this responsibility. In Baden-Württemberg, the crisis cell (or emergency task force) is formed by employees of the environment ministry supported by expert advisors, whose names are not usually made public. In real emergencies, crisis cell members communicate with NPP operators and make recommendations to the political branch of the government in charge of implementing protective countermeasures. Emission data are provided by NPP operators, the INIS network, and BfS helicopters equipped with mobile emission measurement devices. The crisis cell has four subunits, for nuclear protection (Unit-N), coordination and logistics (Unit-K), technical assessment of the affected NPP in the course of the accident (Unit-T), and radiation protection (Unit-S). The 12 members of Unit-S and those of Unit-T are either natural scientists (i.e., physicists, chemists, etc.) or engineers. Unit-N, composed of administrative staff and politicians, takes the final decision upon the recommendations which are forwarded to the team in charge of implementing the countermeasures. The Minister of the Environment makes public announcements about eventual countermeasures. In total, the crisis cell is composed of about 40 people. The main purpose of the ABR-KFÜ system used by Unit-S is to automate calculations and data transferring tasks carried out manually before its introduction. In a real emergency, the system is either triggered automatically when measured emission values exceed a certain threshold or when the NPP operator signals a dangerous technical incident. Although the simulation programs of the ABR-KFÜ system are usually considered reliable, evaluating the trustworthiness of dispersion forecasts is the most challenging task of the members of the crisis cell. Following an alarm, the crisis cell assembles within 1–2 h in the environment ministry building in Stuttgart. The first dispersion forecasts are used to take decisions upon eventual countermeasures in the 12-sector area around the affected reactor(s). Plausibility checks and mental assessments are performed by the members of Unit-T, who perform an independent cross-check of the recommendations of Unit S. There are basically four possible recommendations that the crisis cell can make for each sector: take shelter, take iodine tablets, and temporary/permanent evacuation. In addition, a 2–5 km zone around the emission point is evacuated regardless of the amount of released substances if an event qualifies as an accident. For evacuations, there exist contingency plans and the actions are coordinated by local authorities from each locality, who may be assisted by police.

The structure of the crisis cell reflects the model of science advisors assisting politicians in the decision-making process. The crisis cell and the decision process are hierarchical and clear to avoid confusion and deadlocks in real emergencies, although, hypothetically, opposition to orders cannot be ruled out. The composition of the task force—with experts having permanent positions and political figures temporary ones—suggests that the accountability for erroneous decisions is strictly political. As atmospheric dispersion models became too complex to allow for manual computations, the ABR-KFÜ system became an *obligatory passage point* in the emergency response processes, recommendations, and actions of the crisis cell. According to Callon [52], an obligatory passage point is a specified course of action (“action program”) constructed around a rationale commonly agreed upon by the actors involved in a certain issue. The rationale for using DSNE systems in preparing for and managing nuclear emergencies is twofold. First, it reflects a feasible compromise reached through changes in legislation and mindset resulted from negotiations between industry representatives and regulators

after the Chernobyl accident. Second, it builds upon the imagination that the residual risks of operating NPPs can be mitigated through atmospheric dispersion simulations, weather forecasts, and an extensive emission sensor network.

### 5.3. Practices of Preparedness: Regular Drills as Rehearsals

Every year another NPP from Baden-Württemberg or one of its neighboring federal states is chosen for a two-day accident simulation. This provides all units of the crisis cell with an opportunity to rehearse their protocols and responsibilities. Preparations for these drills are extensive and follow precisely defined goals and priorities [53]. The summaries of these drills provide insights into the performative dimension of the imaginary of preparedness: the preparations are remarkably precise; the type and location of the imagined accidents is well known long before the exercise; the actors do have enough time to prepare thoroughly; the collaboration and information exchange between different agencies is carefully synchronized. The individual actors and organizations involved in the drills must correlate their actions, which requires an intensive exchange of information. In addition to the drills, the members of Unit-S of the crisis cell meet on a quarterly basis to discuss the status of the ABR-KFÜ system and how to improve the simulation models, visualizations, software, and hardware of the system based on the lessons learned from past drills and the newest developments in the atmospheric dispersion modeling and radiological protection domains.

This thorough organization reflects some features of the sociotechnical imaginary of preparedness: the actors involved in the drills share a belief in the usefulness of meticulous planning and preparations; there exists a practice of gradual improvement from one exercise to another and from one version of the DSNE system to the next; and regular meetings and drills are considered a necessary means for improving preparedness. Jasanoff [33] notes that imaginaries imply agency and drills are meant to roll-out agency in the absence of the actual threat. Although the logic of accidents can only be fully understood post-factum [14], the drills may be regarded as *rehearsals* [26] meant to stabilize the imaginary of preparedness in the absence of an actual threat. In this sense, the regular drills play an important role in a larger context by providing political decision makers and interested members of the public with reassurances that everything is being done to prepare for emergencies using practices rooted in local cultures of political responsibility and accountability.

### 5.4. Imagining Nuclear Crisis Communication

The official nuclear crisis communication guideline [54] by the Federal Commission for Radiation Protection (SSK) describes how crisis communication should be orchestrated to maximize its effectiveness. Each relevant institution, including research institutes, should prepare and rehearse their own protocols for communicating with the public in an emergency. The communication with other public institutions and the media is to be conducted using official statements, press declarations, press conferences, interviews, on-site visits of the damaged facility, discussion rounds in TV and radio shows, etc. Rules for effective communication and measures for assessing its effectiveness are also provided in the guideline. Besides relying on inter-institutional communication channels and the media, the guideline also recommends organizing direct public encounters between “credible risk communicators” and laypersons.

Two assumptions pervade this guideline, reflecting the mindset of its institutional author. One of them is that a deficit of knowledge on the part of the population exists, which needs to be filled by crisis communicators with the help of the media in their attempt to avoid panic and mistrust. In the aftermath of the Fukushima accident, German newspapers have indeed set up impromptu e-learning systems while, for example, the IKA organized two public presentations about the accident with the aim of providing concerned audiences with relevant information about reactor safety and radiological protection. The second assumption is that accidents will follow an orderly six-phase course named “Phase model of the course of a nuclear accident in view of the media coverage” [54]. Starting from these two assumptions, the guideline compares the expected radiological situation and the corresponding

ideal media representation of that information. Two of the projected accident phases reflect additional features of the imaginary of preparedness. During the 'prognosis' phase, the radiological situation is assessed and decisions upon countermeasures are implemented, with the media supporting the work of authorities. The official line of communication is reiterated in broadcasted interviews with emergency managers, politicians, and witnesses. In the 'final' phase, while clean-up works are being conducted, the media becomes a scene of deliberation about the accident's causes, the responsible actors, and the effectiveness of the implemented countermeasures.

The German imaginary of preparedness thus assumes a manageable physical and social world order, with accidents following a predictable course and the media actively helping to mitigate radiological risks as well as to re-establish sociopolitical consensus. In this context, the imagined crisis communication reflects similar beliefs in meticulous planning and orderliness as those shared by the actors involved in the regular drills and exercises using DSNE systems. The imaginary of preparedness thus helps to synchronize the nationwide actions of an entire range of tightly coupled actors, including institutions, task forces, radiation protection units, and media houses by providing hypothetical accident scenarios, which enable such a concerted course of action in the first place. The Fukushima accident, however, showed that, in the age of the Internet and of globalized controversies, many of these expectations will not be met.

### *5.5. Rehearsing Emergency Preparedness in Action*

The Fukushima accident provided German radiological protection experts with a unique opportunity to rehearse the imaginary of preparedness in a real emergency. Although the accident happened thousands of miles away, the experts followed the emergency response protocols, including the guideline for crisis communication, almost as if the accident had occurred in their backyard. During the first weeks after the onset of the accident, senior IKE researchers gathered almost daily in what resembled a crisis cell to discuss the implications of the accident and the official position of the institute for the case that the media requested interviews with them on topics related to the Japanese disaster as well as local preparedness for such an event. Soon after March 11, the Ministry of the Environment of Baden-Württemberg requested that the experts of the ABR-KFÜ group perform a dispersion forecast and dose projection for the Fukushima Daiichi release. Similar requests were received by other institutes in the country to the end of testing and validating the atmospheric dispersion models and DSNE systems used by different institutions and state governments in an immediate emergency. The IKE experts initially relied on emission data received from the German Society for Facility and Reactor Safety (GRS). Yet, given the scarcity of information transpiring from the Japanese authorities [55], the GRS data only provided an estimate of the source term and thus entailed a high level of uncertainty. Consequently, the IKE experts were encouraged to make assumptions concerning the source term as necessary.

As the release from the damaged Fukushima reactors continued, four emission phases from two different reactors could be distinguished. These phases were also visible in the release term compiled by the GRS. The ABR-KFÜ system, however, could only perform simulations for a single emission phase because, in the development of the ABR-KFÜ system, the source terms were based on so-called release categories, which resulted from two outdated German risk studies from 1979 and 1990. Within these risk studies, the worst-case scenario foresaw a maximum release time of 6 h, caused by the hypothetical meltdown of a single core, while assuming a single phase and one source of emission. Although the system supported the input of a custom-made source term, an accident with several emission phases and sources had never occurred and was never considered before in the regular drills. To cope with this situation, the IKE experts modified the models of the ABR-KFÜ system impromptu to support several emission phases. Additional adaptations concerning the range of the simulation models were also necessary. To this end, the model area had to be increased, while the topography of the Fukushima site was converted to a format supported by the system. The required adaptations took several days to implement and the ABR-KFÜ system eventually produced a result, which resembled the

forecasts published by the Japanese authorities. Although an accident with multiple emission phases and sources in Germany or its vicinity would have prevented Unit-S from making recommendations based on dose projections produced by the ABR-KFÜ system in the early phase of a hypothetical accident, experts continued to emphasize the usefulness of the system in follow-up publications [56].

The director of the IKE followed the crisis communication guideline, which recommended that every institute with a nuclear profile in the country organize direct encounters between risk communicators and interested members of the public. Accordingly, on March 25, the IKE organized a public technical presentation aimed at explaining the technical facts about the melting reactors and the radiological situation in Japan. The atmospheric dispersion forecasts produced by the ABR-KFÜ system were presented in arbitrary units because of the uncertainties in the source term. Following the success of the first presentation, which was attended by around 500 people, a second one was given in Stuttgart's city hall. The public rehearsal of the imaginary of preparedness facilitated by IKE's public presentations provided a display of effective direct crisis communication [21].

The IKE experts' reflex to adapt the ABR-KFÜ system impromptu was not unique. For example, Benamrane et al. [55] note that the French operational tools and models were designed to account for mid-range dispersion of 50 to 80 km. Consequently, the IRSN experts had to use "RandD tools" rather than operational ones to produce dose projections during the Fukushima crisis [55]

"According to Didier, an IRSN [Institute for Radiological Protection and Nuclear Safety] expert . . . , the IRSN operational tools were adapted to short range calculations, between 50 and 80 km around the NPP (Tokyo is about 280 km away from Fukushima Prefecture). Therefore, in order to assess longscale dispersion, IRSN worked with RandD tools and also provided the French meteorological center (Météo-France) with release assessments" (p. 245).

Just as in the German case, the French experts conveyed a story of success in subsequent publications although their operational atmospheric dispersion tools were unable to account for an accident of that scale. Such a story appeared in the January 2012 issue of the IRSN magazine [57]. Yet, as opposed to the German report [56], the French story emphasizes improvisation as a valuable emergency response practice, reflecting a fundamental difference in the two countries' cultures of preparedness.

#### 5.6. Assessments and Expectations of Emergency Preparedness

The nuclear emergency response of the Japanese authorities was criticized in the media [21,58,59], by members of the public [22,60], and in different official reports on the Fukushima accident. Some of these reports conveyed contrasting expectations of the role of dose projection systems in real emergencies. Criticizing the performances of the Japanese emergency managers before and during the Fukushima accident, the report of an independent commission appointed by the Japanese Diet [61] notes that due to the "chaotic evacuation orders," some evacuees were sent to areas which later exhibited high levels of radioactivity and that evacuation orders were revised several times in a single day (p. 38). Concerning the Japanese practices of preparedness, the report notes that

"[the] government also failed to assume a severe accident or a complex disaster in its comprehensive nuclear disaster drills. As the scope of the drills expanded, they lost substance, and were performed for cosmetic purposes, rather than to develop preparedness. The irrelevant drills were lacking instruction in the necessity of using tools such as the radiation monitored information from SPEEDI. Though it was applied in the annual drills, participants found the drills useless at the time of the accident" (p. 38).

In support of this assessment, the report invokes the Japanese regulatory guidelines and expectations concerning the role of DSNE systems, which align well with the ones used in Germany:

"The Emergency Response Support System (ERSS) and the [System for Prediction of Environment Emergency Dose Information] SPEEDI are in place to protect public safety. The environment

monitoring guideline assumption is that ERSS predicts and forecasts the release of radioactive substances and release data, and SPEEDI predicts and forecasts the spread of radioactive materials based on ERSS. Public safety measures, including those for evacuation, should be planned based on the use of these systems [ . . . ].

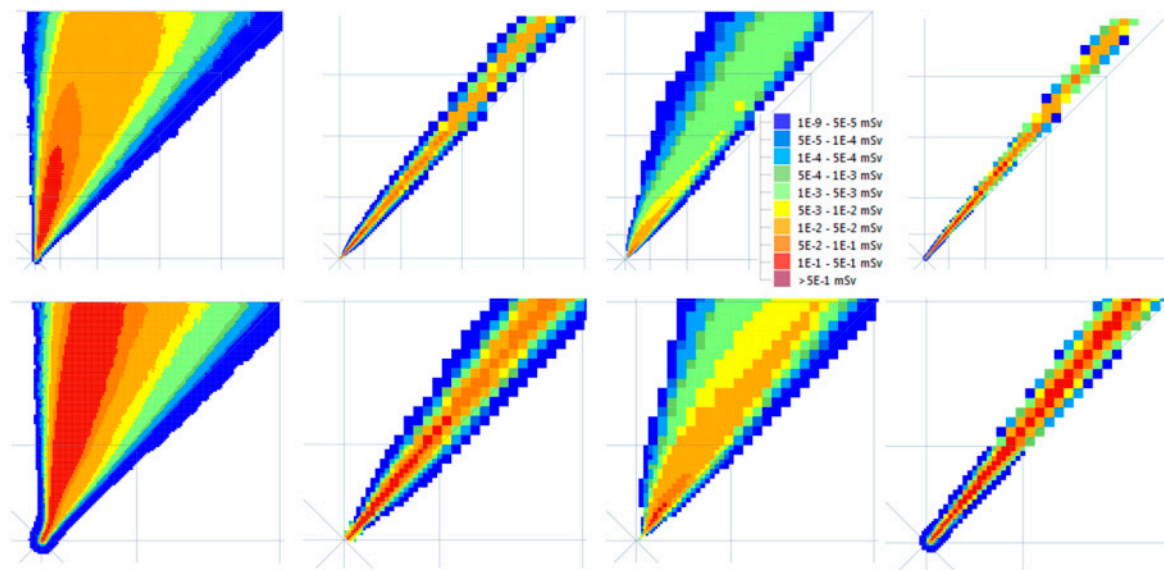
The system failed. The emission data could not be retrieved from ERSS, and the government was unable to use the SPEEDI results in planning protection measures and fixing evacuation zones.” (p. 38).

Without taking into consideration the circumstance of the situation, notably the lack of measurement data and the inherent limitations of atmospheric dispersion models and dose projection systems, the Independent Commission’s report reflects the expectation that DSNE systems should be used operatively during a real emergency for determining evacuation zones and other aspects of the different countermeasures. This assessment contrasts the IAEA guideline for nuclear emergency preparedness and response [62], which recommends that simple criteria relying on measured data and not on dose projections be used in the decision process in the early phase of an accident, considering that such projections may entail “great uncertainties” before and during a release (p. 286). Consequently, the IAEA report [63] on the Fukushima accident stresses that, although

“[t]he [Japanese] emergency response plans envisaged that decisions on protective actions would be based on dose projections [using SPEEDI] performed at the time when a decision was necessary ... [t]his approach was not in line with IAEA safety standards, which stipulate that the initial decisions on urgent protective actions for the public need to be based on plant conditions” (p. 44) [63].

The lack of consensus between these two reports can be explained, to some extent, by the different missions of the IAEA and of the Japanese and other national regulatory agencies. While the latter are embedded in local cultures of political accountability, which hold that even unreliable dose projections are preferable to none at all, the IAEA’s position seems to be grounded in its international and professional mission as a promoter of nuclear energy for peaceful purposes and consultant to national governments seeking to develop a sound national regulatory culture that warrants reactor safety.

Shortly after the accident, the German BfS commissioned a comparative study of the atmospheric dispersion and dose projection models used in Germany and Switzerland. The results of this study showed that the forecasts produced by these systems differed both qualitatively and quantitatively in most of the tested scenarios (Figure 3 shows an example). Consequently, the study concluded that different models using identical input and calibration parameters may lead to different recommendations of countermeasures and therefore advised their harmonization on an international level [64]. This conclusion thus shares to a certain degree the concerns of the IAEA regarding the use of dose projection models in the early phase of accidents, while not questioning the overall usefulness of DSNE systems. Rather, it defers the problem of reaching consensus concerning the most appropriate countermeasures based on dose projections to that of improving communication and cooperation between the operators of different DSNE systems. In this sense, the authors of the BfS study call for the alignment of emergency response protocols and procedures across all German federal states and neighboring countries along with more (joint) experiments based on scenarios inspired by the Fukushima accident.



**Figure 3.** Which one to trust? Effective doses projected by four models used in Germany (ABR-KFÜ, ATSTEP, DIPCOT, and RIMPUFF) for an area of  $100 \times 100$  km (top) and  $25 \times 25$  km (bottom). Source: (the Federal Office for Radiation Protection (BfS), 2016).

## 6. Discussion

This paper argued that, in Germany, the sociotechnical imaginary of containment was challenged by the anti-nuclear movement and the radiological effects of the Chernobyl accident, which left room for another imagination in its place. With the proof that radioactivity could not always be effectively contained within the reactor, a shift in German nuclear risk culture occurred, emphasizing mitigation rather than prevention. Thanks to the financial support of the nuclear industry and the German federal states, a new imaginary of nuclear emergency preparedness developed around existing practices of monitoring the radioactivity around NPPs and new simulation-based decision-support systems for nuclear emergency management. By promising effective risk mitigation in addition to prevention, the imaginary of preparedness aimed at reassuring Germans of the joint capacity of the authorities and the industry to protect the population in case of a nuclear emergency thanks to a vast radiation monitoring network, specially designated radiological protection task forces and protocols, and DSNE systems. That compromise facilitated the continued operation of the German NPPs in the context of strong anti-nuclear resentments. After all, as the Chernobyl experience showed, the main nuclear threat came from abroad, while German reactors were considered relatively safe. Culturally, the new imaginary was sensible of the public expectations concerning political accountability and responsibility for radiological protection after the events of 1986, while preserving the vision of a feasible near to mid-term future for nuclear technology in that country. In this sense, the imaginary of preparedness did not dissolve, but extended the scope of containment, from inside the reactor to its environment. Preparedness meant both containing radioactive substances as far as possible and limiting their effects in case of an accidental release. Preparedness reflects a kind of fault tolerance principle, which is insensible to the perpetrator of the consequential failures of those faults. The imaginary of preparedness thus touched a sensible key in German technopolitical culture, where the “perpetrator” principle, which holds the entity causing a risk accountable for all of its potential consequences, stands at the core of the policies aimed at regulating risky technologies. The shift from the zero-risk mindset of the imaginary of containment towards preparedness for nuclear emergencies described by Schmid (2013) in the Japanese context thus appears to have occurred in Germany almost three decades earlier.

The lesson learned during the Fukushima accident about the ERSS, SPEEDI, and ABR-KFÜ systems point to the inherent uncertainty and potential confusion underlying the use of computer models for the immediate assessment of the radiological situation in a real emergency. These concerns were confirmed

by the BfS study of German dose projection models. The Fukushima experience thus contrasted the German imagination of preparedness which expected nuclear accidents to follow an orderly course of events and to have predictable effects. The mitigation technologies designed to be more objective non-human experts assisting emergency managers needed to be adapted ad-hoc to account for an unforeseen multi-source and phase release accident. The expectation that, in a real emergency, the first dose projections produced by DSNE systems around the country would be released by experts within the first hours from the onset of an accident proved to be unrealistic. More importantly, as the Japanese case showed, the expectation that computer-generated dose projections would be used by emergency managers to plan evacuations and other countermeasures without questioning their reliability and trustworthiness also proved naïve. The Japanese and German responses to the Fukushima accident thus revealed the limits of preparedness in its currently imagined form.

The impression, conveyed by the Japanese Diet's report on the accident, that preparedness failed because dose projection systems failed, should, however, be interpreted in a more nuanced fashion, since—as the IAEA report and members of the atmospheric dispersion modeling community point out [55]—the inherent limitations of atmospheric transport and dispersion models were well known before the accident. In this sense, it would be more accurate to say that the Fukushima experience provided a compelling display of how emergency preparedness can be perceived as having failed due to the misalignment of public and political expectations of preparedness in an immediate emergency, and the inherent limitations of the practices and technologies of preparedness envisioned in the 25 years after the Chernobyl accident. A reflection along these lines can also be read in the report of the “Ethics Commission” appointed by the German Chancellor shortly after the Fukushima accident to assess the opportunity and feasibility of a nuclear phase out in that country [4]:

“In a highly organized high-tech country like Japan, the nuclear accident in Fukushima shows the limitations of human disaster preparedness and measures in an immediate emergency. Impacts of all kinds that cannot or can hardly be contained occur for nature and food production, for the local people and for the global economic. ( . . . ) If the last serious [accident] case is excluded, safety concepts lose their verifiable rationality. The risk cannot then be derived from experiences with real accidents because the consequences of a worst-case nuclear accident are unknown or can no longer be tracked” (p. 31–32, in the author's translation).

This report is important for understanding the rationale for the German nuclear phase-out because it elaborates on the main arguments that stood at the basis of that decision. In this sense, it is noteworthy that, among other prominent figures, the commission included the two leading German risk researchers, Ulrich Beck and Ortwin Renn, who have long-sustained opposing positions regarding technological risks in their works—with Beck being rather categorical in assessing those risks in a critical sociological tradition and Renn (a sociologist himself) promoting a relativist risk assessment approach based on comparing the risks and benefits of all the available energy sources at a given moment. While the composition of the commission has been criticized for excluding members of the Green Party and of the anti-nuclear movement, having Beck and Renn at the same table agreeing on the necessity of phasing out nuclear energy represented a strong signal of transition towards a new culture of risk assessment grounded in consensus, not opposition between the two stances. However, it must be stressed that the categorical argument reflected in the quotation above appears to dominate the commission's conclusion, within which the relativist perspective is only invoked to assess that alternative energies entail lower risks than nuclear power on the long term and that Germany has the innovative, social, and economic capacity to compensate for the nuclear phase out.

Benamrane et al. [55] note that atmospheric transport and dispersion models have improved considerably over the 25 years between the Chernobyl and Fukushima accidents in terms of how measured data and weather forecasts are being used and how uncertainty evaluations are performed. These authors also stress the importance of experts in assessing the plausibility of model results. However, I would argue that the issues raised by the categorical assessment of nuclear preparedness in



Germany also concerned aspects that cannot only be addressed through uncertainty quantification and model improvements. Rather, they seem to be grounded in the inherent limits of representation—to use Kinella’s [50] term—concerning the worst-case accident scenario. Therefore, I would argue that the users of such models and of DSNE systems, who may include the modelers themselves but, primarily, emergency management experts and decision makers, should allow for some improvisation, as Schmid [2,25] suggests, as part of emergency response protocols.

From a practical perspective, one should expect that atmospheric dispersion models and DSNE systems might have to be adapted impromptu to cope with the uniqueness of each accident. Hence, they should be rendered more flexibly adaptable, less tightly coupled, more easily reconfigurable, and more transparent for experts, who inherit legacy models and system components, some of which date from the 1980s. As I have pointed out elsewhere [65], these issues require a change of mindset towards accepting “non-knowledge” about the worst-case scenario as an inherent component of emergency preparedness cultures in addition to the concepts of risk and uncertainty. Such a change would require the revision of emergency protocols to explicitly allow for a period of adjustment of models and systems before the first results are used for decision making. Moreover, in the age of the Internet, crisis communication strategies should be revised so as to take into consideration unofficial radiation measurements and maps produced by media outlets and members of the public. In this sense, the following open questions remain: How can alternative sources of information be leveraged rather than mitigated in nuclear emergencies? How can atmospheric dispersion models and DSNE systems be rendered more easily adaptable in a real emergency? And how can improvisation be legitimized as a useful emergency response practice in cultures that value meticulous planning and rigid protocols?

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