Atomically Entangled Futures: the Role of Accident Tolerant Fuels

Exploring Nuclear Discourse through a Material Social Futures Perspective

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This thesis is dedicated to the memory of my grandparents
—my 奶奶, 爷爷, 姥爷, and 姥姥.

“...unless the past and the future were made part of the present by memory and intention, there was, in human terms, no road, nowhere to go...”

Ursula K. Le Guin, *The Dispossessed* (1974)

Declaration

I declare that the work presented in this thesis is my own, and that where the work of others has been used, I have given credit where it is due. This work has not been submitted, in whole or in part, for any other degree or professional application.

The following chapters contain work that has been published:

- Chapter 4, which contains work from: J. J. Li and S. T. Murphy, “Diffusion in hypo-stoichiometric uranium mononitride”, *Prog. Nucl. Energy*, vol. 142, p. 103 995, 2021
- Chapter 5, which contains work from: J. J. Li, N. Zagni, W. D. Neilson, R. L. Gray, and S. T. Murphy, “The incorporation of xenon at point defects and bubbles in uranium mononitride", *J. Nucl. Mat.*, vol. 586, p. 154656, 2023

Abstract

Nuclear power has played a crucial role in the past century, ensuring energy security due to its reliability and supporting the response to the ongoing climate crisis. However, certain events have forced the nuclear industry to reflect on how best to improve their technologies. The Fukushima Daiichi accident in 2011 spurred the industry to research and develop Accident Tolerant Fuels (ATFs)—fuels that have increased safety margins in accident scenarios where the coolant has been lost. One such ATF is uranium nitride (UN), the properties of which are relatively unexplored. The thermophysical properties of UN have been modelled, as well as the diffusion of nitrogen atoms via point defects to determine how stoichiometry impacts activation energies. The aggregation of fission gas bubbles in UN voids was simulated, focussing on xenon. The findings indicate that under high pressure, xenon bubbles do not undergo thermal resolution, rather, the UN lattice prefers to deform. Such results give a greater insight into the behaviour of UN under accident conditions.

With events shaping how we experience, understand, and make meaning of nuclear power, this results in ever-evolving discourse around nuclear power. Through interviews with nuclear power stakeholders, in which future technologies like ATFs were discussed, a multitude of themes have emerged, from which a creative-critical future has been constructed. This thesis exemplifies how the material and social science disciplines are inextricably linked, and makes the case for those in often isolated disciplines to take a broader approach with their studies. Through a unique interdisciplinary perspective, the material social futures of nuclear power have been explored to highlight the importance of conducting holistic research in order to better examine our perceived nuclear power futures.

Acknowledgements

Upon reflection, my PhD journey was a transformative one. A large part of my PhD took place during the COVID-19 pandemic, which brought huge changes both globally and personally. However, over the course of my PhD, I was able to move to and explore a new area of the UK, and meet lots of people who have shaped me and my research.

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Lastly, but certainly not leastly, I would like to thank my partner Aiham for his encouragement throughout the PhD and beyond, who at the time of writing this is helping me double check my citations. His unwavering love and patience has carried me through these past few years and I am forever grateful for his presence in my life. I look forward to making many more decorative focaccias together and winning at board games.

Contents

List of Acronyms

AGR Advanced Gas-cooled Reactor

AI Artificial Intelligence

ANT Actor Network Theory

AONB Area of Outstanding Natural Beauty

ATF Accident Tolerant Fuel

DFT Density Functional Theory

FL Futures Literacy

GDF Geological Disposal Facility

LOCA Loss Of Coolant Accident

MD Molecular Dynamics

TEPCO Tokyo Electric Power Company

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Introduction

Entering the front door of your home, you turn on the light before throwing your keys on the table. Heading into the kitchen, you switch on the kettle and wait for the water to boil for a much-anticipated brew. It's a cold winter's evening, so you put the heating on and the temperature of the house slowly creeps up. Looking forward to a quiet night, you turn on the TV and start charging your phone, ready to reply to all the messages you missed during the day.

Such a scenario shows how energy facilitates our lives, and how being "switched on" is a constant in the day-to-day; an electrification of our human experiences. The use of energy has defined societal advances and cultures. From the discovery of fire, to large-scale industrialisation, discourse and narratives have been created around how energy is harnessed and the unfolding social changes as a result. Culturally, energy and human behaviour have been entangled. As humanity has changed and adapted with the widespread use of electricity in the recent centuries, societies, particularly those in the West and Global North[1], have become more energy conscious. From "eco" technologies and "smart", energy-saving devices, the journeys of energy from its source to its point of use have become increasingly visible and embedded within society. Nowadays, certainly in the United Kingdom, it is common to switch on a washing machine and watch as a smart meter calculates and displays the financial cost of running a laundry cycle, or baking a cake in the oven, or using the

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[1] In referring to the 'Global North', I use this term as a geopolitical construct that indicates countries and regions who hold power and are major beneficiaries from global capitalism. In the context of energy, humans' experiences of energy in these rich, capitalist regions differ from those where rapid industrialisation occur, though massive inequalities still exist in respect of people's access to energy.

dishwasher to wash your dishes.

Ensuring the security of global energy supplies has become increasingly crucial for energy consumers owing to the devastating impacts of the climate crisis and the far-reaching effects of geopolitical events. Growing carbon emissions from the large-scale use of fossil fuels for energy generation drives much of the climate crisis, which expands the interactions between the human and the non-human. Our dependence on fossil fuels has set the foundations for our lives; Chakrabarty writes, "[t]he mansion of modern freedoms stands on an ever-expanding base of fossil-fuel use" [1]. Clean energy alternatives to fossil fuels have emerged throughout the past century, in part an effort to combat the climate crisis and to steer away from an over-reliance on fossil fuels. For the UK in particular, its energy mix is bolstered by a wide variety of energy sources, such as wind, solar, hydropower, and nuclear power—largely considered to be vital for attaining a zero carbon future.

Currently, nuclear power is responsible for supplying approximately 15-20% of the UK's daily electricity supply through its ability to provide a stable and reliable source of electricity. The nuclear power industry has experienced accelerated growth into its research and technological development over the past few decades, and many more reactor projects have been scheduled in the UK. However, with failures and delivery delays in nuclear power impacting public attitudes and perceptions [2], the future of nuclear power becomes more uncertain. If the nuclear industry is to continue and grow, the multi-faceted challenges arising from the material and social interconnections of nuclear energy must be examined through an interdisciplinary lens to address the social concerns of nuclear power.

The work in this thesis has been conducted according to a Material Social Futures perspective – an interdisciplinary approach that analyses how material developments and societal change inform each other. A fundamental notion of the Material Social

Futures perspective is the idea that every material product or implementation is accompanied by a social cost[2]. For example, the end of life of electronic devices such as laptops and mobile phones is situated in e-waste dump sites such as Agogbloshie, Ghana, among many other countries in the Global South[3] who disproportionately bear the social costs of materials. Such constructed realities, alongside other themes of global political ecology, will be explored in this thesis.

In this thesis, I am employing a combination of approaches to nuclear power and its material social futures. I have undertaken a computational analysis of the behaviour of uranium nitride and accident tolerant fuels, and I have conducted a qualitative analysis of nuclear energy, involving interviews with a variety of key stakeholders in the nuclear sector and nuclear activists. In the final stage of the thesis, I go on to combine the insights from using both a classical sciences methodology of computational analysis with qualitative data to project a speculative snapshot into what a possible nuclear future might look like.

The structure of this thesis follows the pattern of a thesis in the materials science discipline, where my introductory sections are numbered, and the content chapters that one would expect to see in a humanities thesis are subsumed within a broader numbering system. Such chapters begin with Chapter 3, which contains research into societal narratives around nuclear power technologies through the discourse analysis of stakeholder interviews, from which themes have emerged. Chapters 4 and 5 focus on nuclear material science, and contain research involving atomistic simulations of the physical properties of uranium nitride, as well as the behaviours

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[2] There is an argument to be considered here that there are also social affordances to materials. However, a central point of this thesis is that our current method of researching, developing, and producing materials almost exclusively focusses on what they can provide and do for us, which is especially emphasised in the context of a profit-driven, perpetual growth society where materials are used for convenience to facilitate our fast-paced lives. Very little discussion is given to the social costs of these materials, so this thesis focusses on the importance of evaluating the social costs of nuclear materials.

[3] I use the Finance Center for South-South Cooperation's list of countries in the Global South [3], alongside Haug, Braveboy-Wagner, and Maihold's interpretation and examination of the term [4].

of fission gas atoms inside this fuel. The work in Chapters 4 and 5 has been published during the course of this thesis, and evidence the potential of uranium nitride to be employed in fission reactors. In the final chapter, Chapter 6, a creative-critical future is presented, using the findings in Chapters 3, 4, and 5. Essentially, the background in this thesis and the work presented in Chapters 3, 4, and 5 build towards the futures work in Chapter 6, an instance of interdisciplinary praxis entitled “A Nuclear Future". In doing so, I aim to exemplify how future fictionalisations can feature seriously in policy and strategy work, as they do currently [5, 6]. Between chapters, and indeed within chapters, the reader may at times feel discontinuous jumps between topics; such juxtapositions are to be expected in an interdisciplinary thesis and benefit the holistic research that comes about from using Material Social Futures perspectives and frameworks.

Ultimately, this thesis will offer a unique perspective into the inextricable links between nuclear power, society, and culture and seek to encourage the use of holistic and interdisciplinary methods of futures thinking in energy technologies to empower vigilance in the face of inexorable uncertainty. This is to answer the overall research question of this thesis: “*Can a creative-critical future be produced using a Material Social Futures perspective, and what will that look like?*". Currently, our journey has just begun in this introductory chapter, as can be seen in Figure 1. In the next chapter, I will detail the background of this thesis, and discuss nuclear fuels, attitudes towards nuclear power, and nuclear futures.

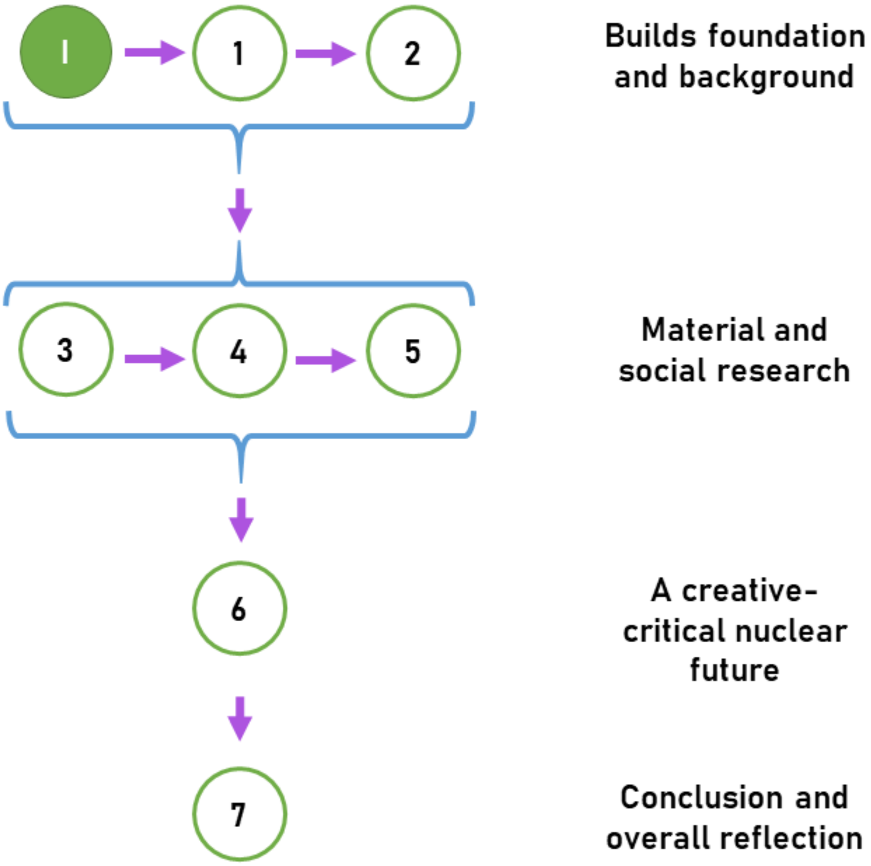


Figure 1: A map of the thesis structure. Where we are now ('I') is an introduction to the overall thesis, leading to Chapter 1, the background chapter.

Chapter 1

Background

In the previous chapter, I introduced the thesis at a high level and set out what the reader can expect to see over the coming chapters. In this chapter, I will discuss the historical context and societal attitudes around nuclear power, as well as nuclear futures.

In this thesis, the principles of the interdisciplinary Material Social Futures perspective is delivered using an integrative approach. Not only does this thesis demonstrate the importance of a less siloed process of doing, presenting, and engaging with research, it also highlights the opportunities to comprehensively explore around and within complex technical, social, and political paradigms such as nuclear power. This thesis rejects any move to separate materials and humanities studies, as materials research is intrinsically embedded in our culture and our emotional worlds. It is a matter of ensuring that researchers understand the significance of nuclear power in the social realm, outside of the confines of pure materials science research.

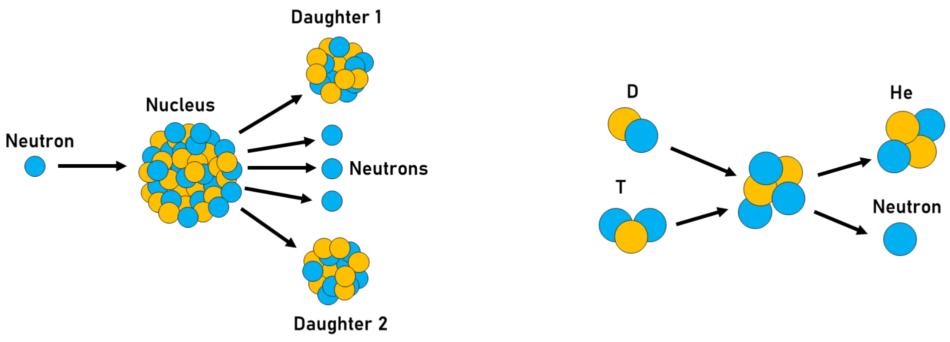
This thesis as a whole is to be read and understood by various audiences. The anticipated readership of this thesis will involve current and future researchers, as well as members of the public who are interested in energy societies and futures. I envision that for scholars especially, this thesis will be part of the precedent for research systems of the future. I have endeavoured to make this thesis accessible to multiple audiences because I believe that interdisciplinarity has great value in eliminating barriers to wider thought and conversation around energy materialities, and to gain various insights at the interfaces between disciplines.

At times, there will be topics included in this thesis that can be considered to be out of the scope of this research, such as coloniality and gender. Although these topics may be important, relevant, and interesting to pursue, I have simply provided high level discussions to give more focus to the more pertinent areas of my research.

This thesis consists of three major components. One, which is the investigation of uranium mononitride— an accident tolerant nuclear fuel—through computational modelling, is a materials science research component, and is placed in conversation with the social and political ecology of nuclear fuels through analysis of qualitative research undertaken with nuclear sector stakeholders and nuclear activists. Finally, these two elements are placed through the process and medium of speculative, creative-critical futures work. Given that this thesis encompasses both material science and social science research into nuclear power, this chapter aims to provide an expansive overview into the principles and foundational understandings of material and social aspects of nuclear energy, and delve into the theoretical underpinnings of futures thinking methods.

1.1 Nuclear power

The essence of nuclear energy lies in two physical processes: fission and fusion, which are shown in Figure 1.1. For fission to occur, a neutron must collide with a heavy nucleus, which splits into lighter daughter nuclei and further neutrons, corresponding with a release of energy. The neutrons that are released then proceed to collide with other nuclei in a chain reaction. Fusion, on the other hand, involves joining small nuclei together to form a heavier nucleus and release energy, much like the processes that occur in the centre of the Sun. The utilisation of nuclear fission dates back to the 1940s, firstly in atomic weapons and then in power plants soon after, whereas the commercialisation of fusion has faced difficulties due to challenges in confinement and higher fuel temperatures [7].



(a) (b)

Figure 1.1: Diagrams showing the processes of fission (a) and fusion (b). In (a), the daughter nuclei are known as ‘fission products’.

Generally, a nuclear fission reactor works by using the energy from the reactions to create steam, which turns a turbine that drives a generator. The fuel in the reactor core is surrounded by a coolant, which acts as a heat exchanger, taking thermal energy away from the fuel. As the fission reactions occur, the fast neutrons come into contact with atoms in a moderator, which slows neutron speeds to ensure a higher likelihood of fission occurring, quantitatively described as an isotope‘s fission cross section. Control rods, made of hafnium, cadmium, or boron carbide [8], are inserted into the reactor core as a neutron absorber in order to regulate the rate of fission reactions, and therefore the energy produced in the reactor. As a fission reaction progresses during operation, fission products accumulate in the fuel. As a result, the chemistry of the fuel undergoes significant changes, which are deleterious to the properties of the fuel.

Worldwide, there are over 400 operational nuclear fission power plants that together avert around two billion tonnes of greenhouse gas emissions annually [9].

There are various types of fission reactors, differentiated by their designs, sizes, or coolant and moderator types. The most common type is the Pressurised Water Reactor (PWR), where water is kept at pressure in a primary circuit and steam is generated through a heat exchanger in a secondary circuit. Slightly less common than PWRs, the Boiling Water Reactor (BWR) boils water directly in its primary circuit. PWRs and BWRs are classed as light water reactors (LWR) due to using water of normal chemical composition as both a coolant and moderator. In the UK, the most common reactor design is the Advanced Gas-cooled Reactor (AGR), which uses graphite as the moderator and carbon dioxide as the coolant. Other reactor designs include those under the umbrella notation Small Modular Reactor (SMR), which are smaller in size and are of a modular design [10], and the Molten Salt Reactor (MSR), which uses liquid salt as its coolant [11]. Highly advanced reactor designs have been proposed for future fission reactors, and will likely see further research and development in the coming decades.

The various meanings of nuclear power in the social consciousness encapsulate numerous material aspects of nuclear energy and their affective attachments. Peoples builds upon Hecht's idea of "nuclearity" as a technopolitical phenomenon[1] [12] by evaluating interpretations of life and death in the nuclear age [13]. He finds, through analysing theoretical reflections on nuclear technologies, that there are dualities in the nuclear age, propelled by utopian visions of nuclear power, as well as tensions arising from the technological incorporation of nuclear energy for "life-destroying and life-sustaining tendencies" [13]. Indeed, in the first scientific paper to propose nuclear fusion, published in 1920 [14], astrophysicist Arthur Eddington wrote that:

> If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race—or for its suicide.

From its characterisation as a limitless and inexhaustible source of power in the

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[1] Hecht explains technopoliticality in terms of the intricate causalities between the technological and social aspects of a particular material object [12]

early twentieth century to its more recent role as an effective technology in combating climate change [15, 16], the many framings and representations of nuclear power have, in addition to being important for the nuclear industry, aided in the development of its societal associations [17]. As described by Caputi in her examination of principle understandings of nuclear power, the "nuclearisation" of contemporary life and the patriarchal metaphors of nuclear power have shaped nuclear discourse[2] [18]. Moreover, Kimura touches upon Salleh's review into the culturally constructed language of nuclear power, finding that "a masculine logic of domination in the nuclear sector was inherently destructive and anti-women" [19, 20]. More broadly for climate change, ideas have been formulated around evoking certain images and emotions of climate change to mobilise younger generations, with a Japanese environment minister declaring that the "climate fight [must be made] 'sexy' and 'fun'" [21]. With the environment undergoing extreme changes along with our attitudes towards new developments, how might new nuclear technologies fare in the affective sense?

As a good nuclear counterpart to accident tolerant fuels, nuclear fusion can be considered to be a paradigm for new nuclear technologies that are expected to be widely implemented, along with its own material and social costs. The inclusion of nuclear fusion in this thesis is not to draw focus away from accident tolerant fuels, but to highlight its existence alongside them; nuclear fusion will therefore be discussed in this thesis at a high level. In the 1950s, researchers first proposed the concept of the tokamak: a device that uses magnetic fields to confine plasma [22]. Today, records have been set for sustained fusion reactions; the soon-to-be decommissioned Joint European Torus (JET) experiment produced 59 MJ over 5 s in 2021, almost doubling the energy produced in 1997 [23]. Extensive research and development into

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[2] In *The metaphors of radiation: Or, why a beautiful woman is like a nuclear power plant*, Caputi draws links between the patriarchal domination of nuclear power through sexualisation (Caputi terms it "nuclear pornography") and the technological aspects of nuclear power. For example, Caputi discusses how actor Rita Hayworth, in a sexualised capacity, was painted on the side of an atomic weapon nicknamed 'Gilda' that was detonated over Bikini atoll. Additionally, she discusses the metaphorical eroticism of nuclear power, in that male sexuality is often linked to reactors 'blowing', whereas female sexuality is often linked to containment and control [18].

nuclear fusion has taken place. However, there are currently no commercially operating fusion plants, therefore the societal incorporation of nuclear fusion is not able to be assessed in its totality. Nevertheless, for nuclear fusion, it has been found that lay knowledge of fusion technologies is limited, and that familiar reasoning of the "nuclear" term is used to analogise fusion and fission; additionally, there is a greater desire to learn about fusion in the siting context as "the technology comes closer to people's lives" [24]. Interestingly, journalists reporting for Belgian media frequently mistook fusion for fission, indicating the propensity for confusion between the two technologies [25]. In public responses to the proposed use of depleted uranium[3] as storage for radioactive tritium, Jones, Yardley, and Medley noted the stigmatising effect of the term "depleted", and found that clarification and further information on depleted uranium was able to have a reparative effect on the misconceptions, demonstrating the impact of public engagement on the acceptance of new technologies [27].

Similar to the findings of Prades López *et al.* [24], Turcanu *et al.*'s qualitative-quantitative study into public understandings of nuclear fusion revealed a tendency for fission to be used in a comparative way in order to make sense of nuclear fusion [28]. From their findings, Turcanu *et al.* conclude that engagement efforts around nuclear fusion for the general public should focus on enabling learning to occur through terms relevant to lay people, and push beyond the deficit model[4] to adopt better approaches to communication. These findings were found to agree with Čábelková *et al.*'s results, which suggest that public acceptance for nuclear fusion requires more communication, as well as media framings of fusion issues to be relevant to the layperson [30]. Extending these conclusions for nuclear fusion to new nuclear technologies as whole, it is evident that efforts must be made in constructing inclusive relationships with the general public in order to empower their ability to make sense of new material realities, as well as for determining the social futures of

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[3] A by-product from enriching uranium, depleted uranium contains a lower concentration of the fissile isotope ^{235}U than natural uranium, typically $< 0.7\,\%$ [26].

[4] A deficit model refers to ascribing lack of support for a particular scientific or technological innovation to the 'insufficiency' of the public [29].

nuclear innovations. As we have seen from the current literature, it is clear that with the conception of new technologies, or the occurrence of extreme disruptor events such as nuclear disasters, changes in perceived risk and societal associations prompt the emergence of attitudinal shifts, deepening our existing social attachments and entanglements with nuclear power.

1.1.1 Nuclear accidents, associations, and concerns

Human interactions with nuclear materialities have resulted in a comprehensive social history of nuclear power. In discussing the materialities of nuclear power, I refer to the way that the physicalities of materials involved in nuclear power also constitute their culture and social relations, ascribing significance to the social lives of these materials [31]. There is much to explore in the relational and semantic associations that have arisen through the developments and implementations of nuclear energy. In particular, nuclear power accidents have considerably recharacterised nuclear energy and produced shifts in public perceptions of nuclear power. For example, the 1957 Windscale disaster in the UK involved a uranium fire resulting from the reactor core temperature exceeding operational temperatures [32], causing public support to drop, albeit only slightly as the nuclear industry developed good public relations both before and after the Windscale disaster [33, 34]. Similar cases can be observed for other significant events such as the Three Mile Island (1979) [35] and Chernobyl (1986) [36, 37] disasters, as well as the 2011 Fukushima Daiichi [38] Loss Of Coolant Accident (LOCA), which have all been pivotal developments in nuclear history. Of these, the Chernobyl and Fukushima Daiichi accidents resulted in widespread radiation contamination and exposure, which initiated a greater sense of personal vulnerability amongst the affected communities; it is the materialities of nuclear accidents that provoke strong affective connections to nuclear power.

An array of social consequences arises from living with nuclear technologies, in conjunction with affective associations with nuclear accidents. With nuclear power, it is necessary to attain a delicate balance within its systems to ensure the safe operation of reactors. In *Normal Accidents*, Perrow argues that in our technologically-dominated world, there is a general expectation amongst some technical specialists for accidents to occur due to the systems complexity of high-risk technologies [39]. Where nuclear accidents have occurred, it is clear that the meanings of nuclear power are shifted and social relationships with nuclear power ruptured, consequently impacting post-accident convalescence for both general society and industry [40].

Individuals respond to nuclear power according to their personal nuclear narratives and understandings, which in turn are influenced by their social identities—Brown *et al.* remark that risk acceptability is dependent upon an individual's background, present circumstances, and existing knowledge [41]. In turn, public opinion can develop from these social risk assessments of nuclear power, leading to general sentiments emerging and becoming more tangible through movements, such as the Campaign for Nuclear Disarmament, which advocates for the elimination of nuclear weapons and the opposition of nuclear power developments [42]. Within communities living in Fukushima prefecture, women were found to possess a higher level of radiation-related risk perception than men [43], and even more globally amongst science and technology professionals, risk perceptions, alongside trust and environmental values, were found to play a part in the acceptance of nuclear energy [44]. Through focus groups, Ho *et al.* found that amongst Singaporeans, there was generally a conditional acceptance of nuclear power, as well as opposition to nuclear energy developments in Singapore, in part due to risk perceptions from nuclear accidents [45]. In China, where there are over 50 operational nuclear reactors across the country, it was observed that large changes in the perceived risk of nuclear power after the Fukushima Daiichi accident led to increased levels of distrust; this was reflected in the decrease of land prices near power plants, and also in survey responses from a population living near to the power plant closest to Fukushima [46, 47]. For these studies, risk perception levels were seen to recover over time, something which was also observed in Fukushima residents four years after the disaster [48]. In many similar cases, decreasing risk perceptions were largely due to communicative efforts and post-accident support, for example, risk communication was found to reduce radiation anxiety in plant workers [49].

Considering the importance of perceived risk and public opinion in determining the futures of energy technologies [50], it is beneficial to examine the social intricacies within public relationships and attitudes to nuclear power. Various socioeconomic factors, such as alignments with political parties, have been found to impact support for nuclear power [51, 52]. Soni argues that in order to commit to climate change mitigation, governments must proactively share information around nuclear technologies to increase public awareness of the implications of nuclear power [53]; furthermore, when cross-communications take place that involve multiple societal groups, the visibility of public opinion must be taken into account according to Luoma-aho and Vos, who note the imbalances in conversations around nuclear power in Finland: “politicians, power companies and regulators were the ones with voice, as NGOs and citizens were hardly heard” [54].

With nuclear fuels being such a crucial element of the nuclear reactor and of the entire fission process, their makeup and properties have been carefully studied over the past few decades. Generally, uranium is used in fuels as it can be fissioned relatively easily [55]. Currently, the most widely deployed fuel in a fission reactor is uranium dioxide (UO_2), chosen for its radiation tolerance, chemical stability, compatibility with common cladding materials [56], and a high melting point of (3078 ± 15) K [57].

Manufacturing uranium dioxide for fission reactor purposes involves a multistage process. Traditionally, uranium ore is firstly mined using hydrometallurgical techniques such as open-pit or underground methods similar to those used in coal mining [58]. The choice of technique depends on the geological formation of the rock and any other minerals contained within [59]. Where the uranium is near the surface, open-pit mines are created to remove layers of rocks and soil to access the ore below the surface of the earth. Open-pit mining has significant impacts on the environment, degrading air quality and contaminating water sources that in turn affects nearby communities [60]. Where the uranium is located deep underground, tunnels must be constructed to access the rock and remove the ore by drilling [61]. The uranium ore is then milled, where it is transformed into a slurry which is subsequently leached with an acidic or alkaline solution to dissolve the uranium. However, this process has increasingly been superseded by *in-situ* leaching, where an oxidising solution is injected into the ore to dissolve the uranium. The resulting mixture containing the dissolved uranium is then pumped to the surface, leaving the ground largely undisturbed [62, 63]. After the uranium has been extracted, it is then processed into uranium oxide powder, commonly referred to as ‘yellowcake’ [64].

Naturally-occurring uranium contains both ^{238}U and ^{235}U, at 99.28% and 0.715% abundance, respectively [65]. ^{238}U is fertile—it captures a neutron and transforms into ^{239}Pu, which is fissile and can be used as a reactor fuel or in nuclear weaponry [66, 67]. ^{235}U is fissile [68], but as it is relatively low in abundance, it requires enrichment for use in PWR and BWR nuclear reactors where a 3-5% abundance is essential to sustain chain reactions. To enrich ^{235}U, the uranium is firstly converted into a hexafluoride gas, UF_6, which is a solid at room temperature, but becomes a gas when heated. The gaseous form of UF_6 is then rapidly rotated in a centrifuge, where isotopes are separated according to their mass [58]. At the fuel fabrication plant, the enriched UF_6 is converted into a solid in a high-temperature kiln, after which is is pressed into UO_2 fuel pellets [69].

Due to its low thermal conductivity, UO_2 is vulnerable to a rapid increase in centre-line temperature and possible melting during a LOCA, such as the 2011 incident at Fukushima Daiichi. This incident highlighted the need to improve the resilience of fuel materials under accident scenarios. In response, development began on Accident Tolerant Fuel (ATF)s as alternatives to oxide fuels, with higher melting points, thermal conductivities, and specific heat capacities to extend the narrow timeframe available for operators to bring a reactor back under control. Ideally, ATFs would operate in current LWRs and maintain economic feasibility with improved performance relative to UO_2, such as achieving higher burn-ups [70, 71].

In current reactor designs, fuel pellets are stacked inside a cladding tube forming a fuel rod. These rods are then grouped together to form an assembly. Inside the fuel rod there is a gap between the pellet and the cladding, called the plenum, to allow for swelling of the fuel due to high temperatures and incorporation of fission products. This swelling can cause a mechanical interaction between the fuel and the cladding, which can cause cladding breach and contamination of the coolants [72]. As this is extremely undesirable, low thermal expansions are therefore required for ATFs.

Many ATFs have been proposed, such as U_3Si_2, UC, and UB_2 [73]. However, the nuclear technology and fuel manufacturer Westinghouse has chosen to focus on and advance research into developing UN fuel pellets, citing better fuel cycle economics and properties [74].

1.1.2 Uranium mononitride

First developed as a fuel for space reactors in the 1960s [75, 76], UN is a leading ATF candidate for fission reactors. It crystallises in the $Fm\bar{3}m$ space group (No. 225), as shown in Figure 1.2. This rocksalt structure consists of two interconnecting uranium and nitrogen face-centred cubic sublattices. UN exhibits a high melting point of (3120 ± 30) K and a thermal conductivity of 21 $\mathrm{Wm^{-1}K^{-1}}$ at 2000 K [77, 78], compared to a value of 2 $\mathrm{Wm^{-1}K^{-1}}$ for the oxide at the same temperature

[79]. This significantly greater thermal conductivity reduces the rate of temperature increase in the fuel as well as ensuring lower temperature gradients and reduced thermal stresses. Furthermore, the higher uranium density of the nitride—34.2 U atom/nm^3 and 24.5 U atom/nm^3 for UN and UO_2, respectively [78, 80]—offers an economic advantage through minimising the need for enrichment with ^{235}U. However, a complicated fabrication process, requiring enrichment of ^{15}N, coupled with unfavourable reactions with hot coolant water have seen limited application compared to more conventional oxides [81]. It is important that the nitrogen undergoes isotopic enrichment before use in the reactor, as this improves fuel performance over the use of natural nitrogen, ^{14}N. Additionally, ^{14}N is converted to the radioactive isotope ^{14}C during fission, which poses an environmental risk [82]. UN fast reactor fuel ideally requires nearly 100% ^{15}N due to the production of ^{14}C from the reactions of neutrons with ^{14}N [83]. However, in a thermal reactor context, neutrons possess lower energies, and so the conversion from ^{14}N to ^{14}C is less of an issue. In this thesis, a 100% ^{14}N assumption is used.

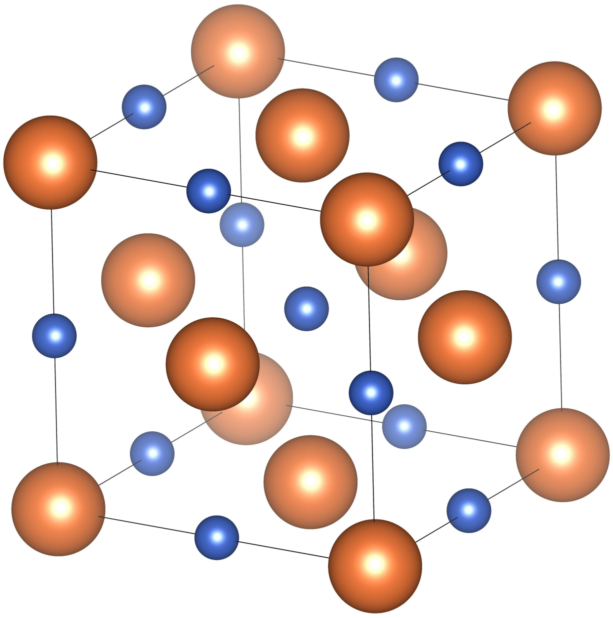

Figure 1.2: The unit cell of UN, showing its crystal structure and atomic arrangement. The larger orange spheres represent uranium atoms, and the smaller blue spheres represent nitrogen atoms.

Several different methods exist for the fabrication of uranium mononitride. These include: the combination of metallic uranium with hydrogen and nitrogen; ammonolysis of uranium hexafluoride, UF_6, or uranium tetrafluoride, UF_4; and the solidification of an aqueous metal solution into kernels [81]. Compared to oxide fuels, nitrides possess high melting temperatures, and so they must be sintered[5] at higher temperatures. It is within the manufacturing stage, in addition to during the material's operational lifetime, where point defects are formed in the material.

Point defects

The stoichiometry of a material is a description of its atomic makeup in terms of relative quantities. Deviations in stoichiometry—non-stoichiometry— are accommodated by point defects, such as vacancies, where atoms are absent from their sites, and interstitials, where atoms occupy the space between lattice sites.

For UN, the vertical line in the U-N_2 phase diagram in Figure 1.3 indicates that at low temperatures, UN is a line compound, where normal stoichiometry is reflected. However, at higher temperatures it is able to accommodate some nitrogen deficiency, becoming UN_{1-x} [84, 85]. This non-stoichiometry is suggested to be accommodated by a combination of antisite defects, where the uranium and nitrogen atoms swap sites, and nitrogen vacancy defects [86]. The significance of such non-stoichiometry resides in the characterisation of point defects as vehicles for transport through lattices, in particular, facilitating fission gas release mechanisms.

Fission gas release

Fission gas release refers to the behaviour of gaseous fission products in nuclear fuels, which can alter fuel performance and degradation [87]. The release of fission gas products, where they travel to grain boundaries and to the surface, can drastically impact the thermophysical properties of the fuel [88]. Fission gas products are able

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[5] Sintering is the process by which powder particles are compacted under pressure to form a solid or a porous material.

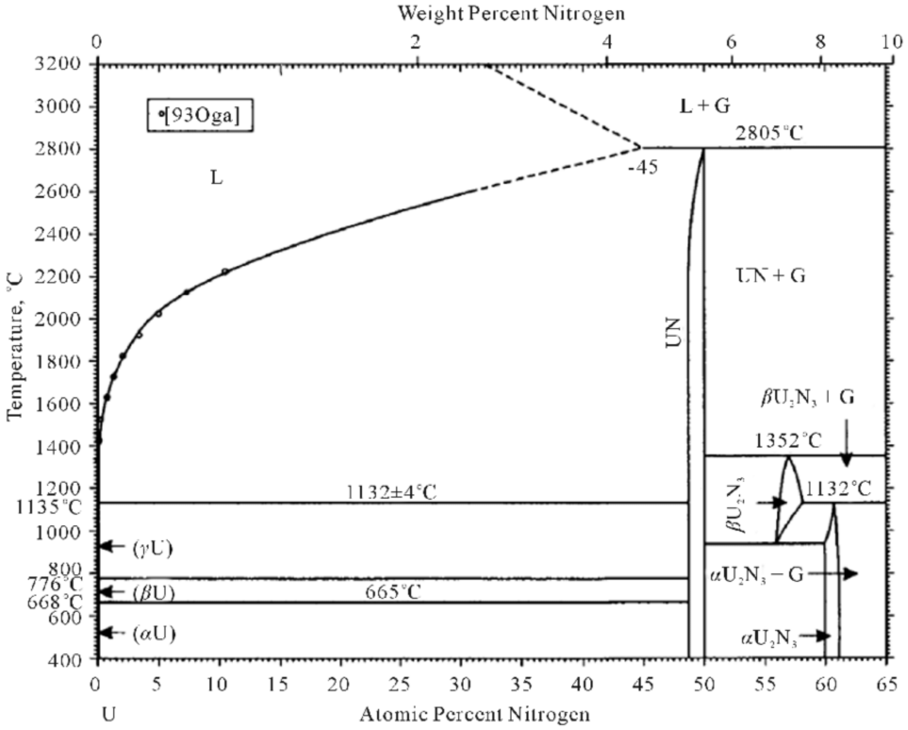

Figure 1.3: A phase diagram for UN, developed by Okamoto *et al.* [85].

to diffuse through the fuel lattice, which is facilitated by point defects [89]. This can lead to fission gas atoms inducing structural changes in the lattice such as swelling [90].

In UO_2, fission gas release has been extensively studied [91], from experimentally studying fission gas bubbles using x-ray absorption spectroscopy and electron microscopy [92–95] and fission product diffusion [96–98], to first principles research into fission product diffusion [99–101] and defect clustering [102–105], to using classical atomistic simulation techniques to study fission gas diffusion [106–109] and bubbles [110–114] in UO_2. Compared to UO_2, there is still much to discover regarding fission gas release in UN. Empirical research into fission gas release for UN has revealed that gas release increases with burnup in UN [115], and that the gas release rate is lower than that of oxide fuels [116] due to its higher thermal conductivity maintaining a lower fuel temperature. However, due to fission gases remaining in the fuel, UN experiences a higher swelling rate during bubble formation [117]. Such impacts arising from fission product behaviour can have detrimental effects on reactor infrastructure, and compromise the degree of fuel containment in the reactor core. Therefore, it is crucial to investigate atomic behaviour within UN, which will be a central point of examination within this thesis.

1.1.3 Nuclear political ecology

Power has been recognised as a critical element to the development of societal relationships, and is central to the field of political ecology [118]; as Huber states: "alternative and renewable energies ... necessitate new and uneven power relations over land, energy, and territory" that lead to unequitable progressions to sustainability [119]. With roots in cultural ecology studies, political ecology is primarily concerned with the control and access of resources and the relationships between society and the environment [120, 121]. There are five central theses to political ecology: degradation and marginalisation; environmental conservation and control; environmental conflict and exclusion; environmental subjects and identity; and the sociopolitical conditions of actors and objects [122]. Whilst political ecology is an eclectic field, Huber contends that a disadvantage to political ecology lies in its treatment of energy as an empirical object, rather than as a foundational concept inherent to our lives and lived experiences [119]. Walker questions the limited presence of the 'ecology' in political ecology, noting that political ecology tends to focus on social science studies on environmental politics [120]. Despite these limitations, as a framework, the praxis of political ecology has been instrumental in explaining and understanding power structures, often through the analytical lens of intersectionality[6].

In essence, political ecology unearths the interactions between materials and society, and as such, has significant overlap with the methodologies employed in this thesis. As energy is a societal necessity, and therefore socially entangled, political

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[6] Originating from Black feminist theory, intersectionality explores the intersections between characteristics such as gender, race, and class, and identifies their interactions with respect to relationships of power and knowledge legitimacy within epistemological structures [123, 124].

ecology can magnify the power structures inherent in energy endeavours and material and social processes. In particular, it highlights the legacy of colonialism; the industrial revolution in the Global North was advanced from the accumulation of wealth from slavery and the exploitation of enslaved people [125, 126]. Political ecology emphasises the dynamics of structural power within a post-colonial context. Hornborg argues that modern energy technologies are “embedded in global flows” of resources and capital, actualised by labour [127]. Furthermore, Domínguez and Luoma elucidate how the erosion of natural environments and Indigenous land rights have been validated through seeing resources and land as sites of control [128]. For nuclear technologies in particular, its material developments have introduced sustained repercussions to society and the environment, for example, in the case of Aboriginal people, reoccupying their land in South Australia after being forcibly removed and inhaling residual plutonium years after nuclear weapons were tested there [129], as well as the physiological impacts of radiation exposure on animals after nuclear accidents [130]. Common to many of these situations is the distance between those in positions of power, and the land, resources, and people they control, strikingly clear through a political ecology frame of analysis. Many industrial companies today, mostly headquartered in the Global North, are decoupled from the consequences of their land dispossession. As a result, their compensatory efforts to mitigate the changes they make lack comprehensive understanding of the problems communities face due to those in power usually deciding compensation, rather than those affected. Additionally, compensation—especially monetary—is often insufficient, delayed, and inadequate in addressing the core issues at hand [131], as seen in the failures for Japan’s electricity distributor, Tokyo Electric Power Company (TEPCO) to properly compensate the victims of the Fukushima Daiichi disaster [132].

There is much value and importance in applying political ecology analysis to nuclear technologies, as it enables critical examination of their material and social impacts, and how they might inform the futures of newer technologies. As Richardson and Weszkalnys write in *Resource Materialities*: "... commodified nature becomes an item of contestation inserted into often deeply unequal and unsettled sets of social relations" [133]. The extraction, use, and disposal of minerals and materials is, therefore, an important avenue of social research. Across the scales and intersections of the political ecology of nuclear power, there are two prominent areas of discussion—uranium mining and nuclear waste, which will be discussed in more detail in the following sections.

Uranium mining

The political ecology surrounding mining sites and procedures requires some examination. Environmental and social identities are ascribed to uranium mining communities through the meanings inherent in the process of mining. A notable example is in the American West, where "yellowcake towns" emerged in the 1950s due to the "uranium boom", experiencing periods of economic prosperity and large fluctuations in population from the establishment and the subsequent stagnation of mining activities [134, 135]. These towns, and the material identities attached to these communities, demonstrate how uranium becomes a cultural resource due to mining [136].

The consequences of poor health from certain processes involved in mining uranium have been widely studied [137–139]. However, political ecology uncovers the imbalances and disparities between different groups involved in mining. Sarkar notes the reliance on Asia and Africa for sourcing uranium due to the lower regulatory standards and lack of decent provisions for workers, and therefore, lower operational costs, ultimately compromising public health [137]. Poor mining practices disproportionately impacted Native communities in the 1950s. In the US, huge quantities of uranium deposits were found on Native American land, belonging to the Navajo Nation, and due to the economic opportunities at the time, many Navajo people worked in the uranium mines. However, the Navajo language did not have a term for radiation, and the workers were not educated by the government and mining companies about the health hazards associated with uranium mining, hence they worked without protective equipment or adequate ventilation. As uranium ore emits radon gas, cases of lung cancer greatly increased amongst the Navajo people from radiation exposure. However, they were excluded from medical studies at the time due to "mathematical precision", instead focussing only on White miners [140–142]. This prevalence of coloniality in uranium mining amongst Native communities can also be seen elsewhere; for example, Caputi writes about how Native reservations, which are often located in economically underdeveloped areas, "have become prime targets for test sites and waste dumps" [143].

Kvanefjeld is a mineral deposit in Southern Greenland containing large quantities of uranium ore. Mining activities began in the 1980s, and over long periods of regulatory changes, the deposit was acquired by Greenland Minerals Ltd, a company headquartered in Australia. In the neighbouring village of Narsaq, residents whose livelihoods depended on farming and agricultural practices came to discover the encroaching impacts of mining at Kvanefjeld; during the operation of the mine, strong winds would blow mine tailings into the village, and farmers found that the livers of their sheep started to turn black [144]. Additionally, as Greenland was colonised by Denmark until 1953 [145], the residents of Narsaq were told that the mine would provide economic independence from Denmark, a claim questioned by some: "... we can't become independent to a company from another country where in the end we lose our right to decide over that land" [144]. After lengthy opposition, Greenland's government subsequently banned uranium mining in Kvanefjeld. Kvanefjeld and its impacts serve as yet another example of how mining produces complex environmental entanglements with society, and especially with the development of newer energy technologies, modern mining practices require much work to be done in promoting balanced approaches to mineral extraction [146].

Over the past few decades, uranium mining has evolved in response to the myriad social impacts of the process of mining, namely health and environmental issues. Uranium mining as an industry has undergone many changes including the introduction of stringent safety measures and is now a regulated industry [147]. This serves to exemplify how the material and social aspects of nuclear power are able to influence each other significantly, and highlights this inevitability when evaluating material impacts.

Nuclear waste

In reflecting upon the current capacity of energy usage and demand, we are confronted with the Jevons paradox: the growing efficiency of technological devices leads to increased energy consumption [148]. This translates into increased resource consumption and consequently, a decline in the quantity of available finite natural resources. Due to a growing concern for this, in many industries the chemical makeup of materials is now more carefully considered at the manufacturing stage, and there is an emphasis on waste management. In a cradle-to-cradle approach[7], waste is seen as food for growth in the realms of intelligent product systems [150]. For nuclear power, however, waste is often viewed as "the most destructive and indestructible waste in history" [151]. Such perceptions, and the nature of nuclear waste, make a cradle-to-cradle design of nuclear power seem implausible. Nevertheless, the nuclear industry has established some practices such as sustainable decommissioning and the reprocessing of spent fuel, with sites and materials repurposed after a plant has reached its lifespan[8] [153], and uranium and plutonium recovered via the Purex process [154].

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[7] A cradle-to-cradle process is where material systems are seen as closed-loop nutrient cycles—at the end of a material's life, the components can be recovered or reused [149].

[8] One example of this is with fast reactors, which use fast neutrons to sustain the fission chain reaction. Nuclear waste contains a vast amount of long-lived minor actinides, and when they undergo irradiation in a fast reactor, they are transmuted into short-lived isotopes and recycled into nuclear fuels [152].

The fuel cycle describes the lifetime of nuclear fuel, from mining uranium to disposal of nuclear waste. For nuclear fuel, an ‘open’ fuel cycle refers to spent fuel that cannot be reprocessed, and a ‘closed’ fuel cycle involves the reprocessing of spent fuel to extract materials that can be used again in the fuel cycle. For high-level nuclear waste that cannot be reprocessed, the industry plans to place the waste within secure storage canisters, and bury it deep in the ground in a Geological Disposal Facility (GDF). However, the burial of nuclear waste has associated challenges, namely, the risk of corrosion and damage to canisters [155]. Many activists and communities have campaigned against the development of GDFs; an example of a highly contested site is the Yucca Mountain storage facility in Nevada. For this repository, the “insurmountable” public opposition to a permanent nuclear waste storage led officials to opt for delaying the decision and instead, store the waste on-site [156]. After the Bush administration gave approval for the disposal facility in 2002, the Obama administration in 2010 reversed the decision following the spending of $12 billion building the site, owing to the “unworkable” opposition [157]. As can be seen from Yucca Mountain, although sizeable investments have been made in developing nuclear waste repositories, social actors can hugely influence the end-of-life of nuclear waste; in 2018, Yano *et al.* found that research and development into nuclear waste was severely underfunded in the US [158], signalling the complexities in nuclear waste sustainabilities, and the social impacts that nuclear waste generates.

From a political ecology perspective, nuclear waste presents many issues in the geographical siting of repositories, especially concerning the use of land for nuclear waste storage. In Liboiron’s anticolonial framework, they outline how “pollution is not a symptom of capitalism but a violent enactment of colonial land relations that claim access to Indigenous land” [159]. As the burial of high-level nuclear waste involves embedding hazardous materials into the environment, there is an aspect of pollution to nuclear waste. It has often been located in proximity to various societal spaces, and within these entanglements exists structural environmental racism and colonialism. For example, in the case of the Skull Valley Goshute Tribe in the US, the tribal leaders made the decision to host high-level nuclear waste on their reservation. In actuality, decades of colonialism forced the Goshute tribe to act within their limitations and to take measures to achieve economic survival within the "landscape of injustice" amidst the large-scale destruction of their environmental surroundings [160]. Nunn sees such encounters as an integral part of toxic geographies, writing that they are situated within "larger histories and constellations of colonial practice that have and continue to produce landscapes of spatial control" [161]. Furthermore, Davies argues that toxic environments are "instances of slow violence"[9], and that framing these toxic environments as "out of sight" invalidates the structural inequalities experienced by the people impacted by the hazardous materials [163]. For hazardous waste removal in particular, Balayannis emphasises the significance of the material properties of waste, arguing that "uncertainty and instability of chemicals" become "a form of environmentally embedded violence" [164]. Therefore, by analysing the impacts of nuclear waste through a political ecology perspective and considering its slow violence, the colonial underpinnings and inequitable ideologies behind its social-material entanglements are foregrounded. In a wider sense, the political ecology of nuclear energy questions our historical scales of power, examining the social actors that affect and are affected by nuclear materialities, and ultimately shedding light on the histories of technological futures yet to come.

1.2 Envisioning nuclear futures

Nostradamus was a French prognosticator who, in the 16th century, published *Les Prophéties*: a book of poems that were purported to predict future global events [165]. His prophecies, which are nowadays viewed with reservation, have been projected far into the future, up until the year 3797 [166]. Although vague, his predictions remain as a prominent example of early futures thinking and visioning.

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[9] Here, Davies uses Nixon's definition of slow violence: "a violence that occurs gradually and out of sight, a violence of delayed destruction that is dispersed across time and space, an attritional violence that is typically not viewed as violence at all" [162].

Nowadays, with futurism and futures research having progressed much since the days of Nostradamus, the persistent pursuit for future knowledge has scarcely diminished, especially with the developments of novel technological innovations.

Forecasting definitive futures is arguably an impossible endeavour and it is only ever a best-guess scenario. Futures thinking groups such as policymakers, military and defense strategists, and meteorologists have needed to confront the complexities that arise from futures multiplicities [167–169]. In order to draw out possible futures, these researchers use different methods to help highlight both prospects and risks for their organisations. Methods such as Driver Mapping[10], which uses the PESTLE (Political, Economic, Social, Technological, Legal, Environmental) system of analysis to identify trends and pathways to futures, have been utilised as vehicles for futures exploration and design. The outcomes yielded from these methods are then used to evaluate possible pathways to the futures, and aid in current action, design, and anticipation. In fact, it is this practice of anticipation that drives many aspects of futures research. Miller notes that Futures Literacy (FL) "is the knowledge and skill of how to 'use-the-future'" [170]. The premise of FL is to provide groups and individuals with the skills and the power to practice engaging with their understandings of futures. I detail some FL methods and their implications in Chapter 2.

1.2.1 Speculative nuclear futures

Speculative and fictionalised futures act as portals into imagined worlds, facilitating predictions in technological and social change [171], as well as disruptive events. To varying degrees, allegories around social futures contain messages relating to material and resource use. For example, the science fiction TV series *Years and Years* depicts the rise of a fascist politician, increasing social unrest, and escalating inter-

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[10] In futures thinking, drivers are situational factors that bring about change and 'drive' the appearance of futures. For example, a driver could be a politician with extreme views coming into power, or the rise of a successful new product on a market. Driver mapping allows for the relationships between drivers to become visible.

national conflict in Britain alongside the advancement of practical transhumanism, use of dirty bombs, and cloud consciousness [172]. *Years and Years* centres much of its narrative around the human experience. By communicating narratives through social themes, this kind of storytelling allows for relatability and applicability within its framing.

Perhaps one of the more comprehensive works revolving around speculative futures is Jonathon Porritt's 2013 book *The World We Made*, which follows a teacher‘s recollections of the decisions that led to the state of the world in 2050 [173]. In this book, Porritt invokes the identity of a 50-year-old history teacher named Alex McKay, who describes various world events that led to present-day life in the year 2050. Porritt makes predictions through McKay's discussions around momentous changes such as global water scarcity as a result of conflicts over water, and famines due to a rapidly-spreading fungus. Throughout *The World We Made*, futures are implicitly carried through significant decisions and watershed events, some of which are attributed to the actions of fictitious characters that act as agents of change. Similarities are noticeable between the character of McKay and Porritt himself; Porritt was previously also a teacher [174], and has throughout his life been closely associated with Green political movements, and McKay is written as an anti-nuclear advocate. He claims that due to cyber terrorism attacks on nuclear power plants, similar to that which disrupted operations at Iran's Natanz plant in 2010 [175], nuclear power was deemed a liability and the "Nuclear Decommissioning Treaty" was established to terminate humanity‘s involvement with nuclear power. This coincided with a general upsurgence in renewable energy production and storage capacity technologies. As a result of Porritt drawing from his lived experiences, McKay becomes a more meaningful envoy of the future, and a more affective representation of technological and social changes.

For nuclear power in particular, its speculative and fictional representations assist in predicting various aspects of nuclear futurism. The 1984 film *Threads* [176], which portrays the survival attempts of UK citizens during a nuclear war, is just one example of a world where nuclearity pervades through the environment and society. Even video games, such as those in the *Fallout* series [177], deal with similar themes of nuclear war in post-apocalyptic future cities. Through these imagined narratives, robust nuclear futures can materialise, opening up further avenues of exploration within each future and beyond. Indeed, burgeoning areas of research in nuclear semiotics[11] have emerged from the efforts and interdisciplinary collaborations between researchers such as linguists, architects, and artists, among others. As languages and cultures develop over time, it is crucial for nuclear semiotics to explore the challenges involved in communicating the issues at hand, and the extent of risk incurred through interacting with radioactive materials. So far, ideas and implementations for nuclear semiotics have included written warnings for buried nuclear waste [178], to cats who change colour when near radioactive material [179]. Others entail intimidating aesthetics such as large spike installations [180], or the presence of nuclear emissaries for the atomic priesthood, modelled from the longevity of the Catholic church's teachings [181, 182].

Whether it is performing bioengineering on colour-changing cats, or a science fiction film about a decommissioned nuclear power plant, every speculative insight into nuclear energy has a powerful ability to add new perspectives to futures planning strategies in industry and foresighting energy futures in policy areas [183–185], allowing us to gaze far into our nuclear destinies. This is why an interdisciplinary combination of methods is crucial; for a multifaceted issue such as nuclear power, the 'blind spots' in the work on ATFs and nuclear narratives are covered by each other, in the sense that implications and consequences that may be hidden are drawn out.

As Miller states, "it is crucial to recognize that the elaboration of exploratory

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[11] Nuclear semiotics is a field of research centred around the development of warning messages for future generations concerning buried nuclear waste.

situations (for human society) is largely a storytelling task" [186, 187]; all futures work is essentially storytelling. Therefore, we must keep searching for our present understandings of nuclear power and its materialities to be able to plan effectively and prepare for the seemingly indeterminable and uncertain roads ahead using existing and imagined narratives.

In this chapter, I discussed the background of nuclear power in detail, and I build on this in the next chapter, as can be seen in Figure 1.4. In the next chapter, I will set out the methodologies that I have used in my work to complete the discussion around the foundations of nuclear power and my research.

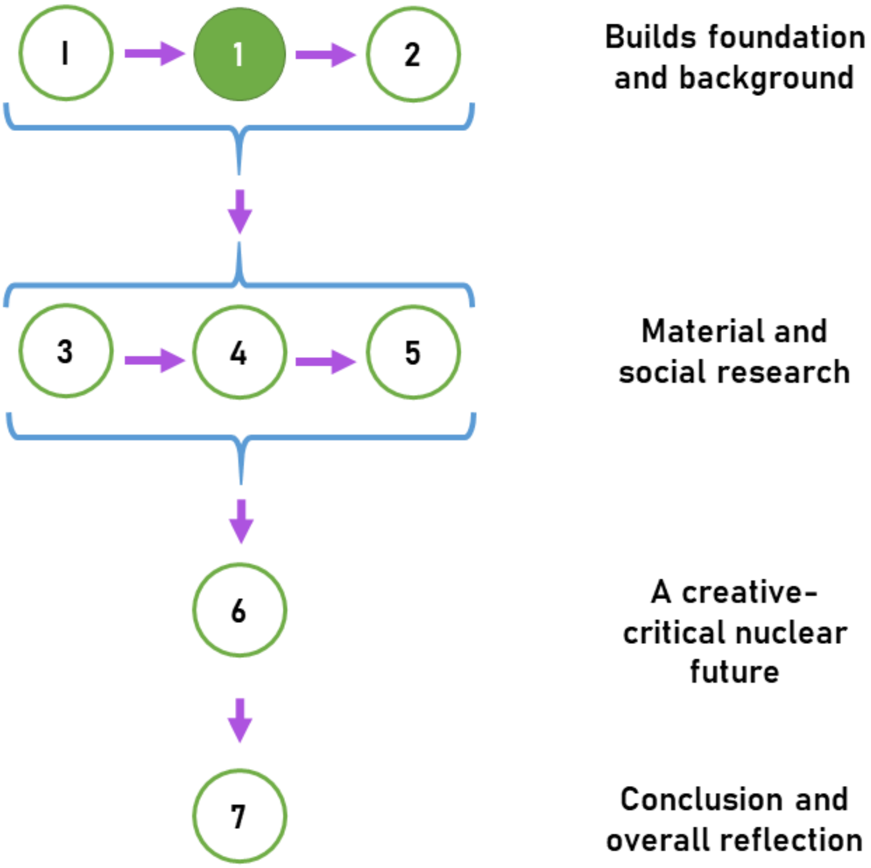

Figure 1.4: A map of the thesis structure. The chapter that we are in now ('1') has provided some background to nuclear power and nuclear futures, which allows us to look at the fundamentals and methodologies used in this thesis in Chapter 2.

Chapter 2

Methodology

In the previous chapter, I discussed the background to nuclear power to provide context to my research. In this chapter, I will set out the methodologies behind my work, which will provide a complete foundation for the original research that I have conducted in the next chapter and beyond.

Before delving into the interconnections between materialities and discourse, I will discuss the influences from Actor Network Theory (ANT). Developed by Science and Technology Studies scholars such as Bruno Latour, the idea of ANT considers notions of impact on the world, and agency from perspectives that are not solely human [188]. For example, if one were to write a book, someone using an ANT perspective would ask what else is involved in the process of writing the book, what role the chair one sits on has in writing the book, and whether the ergonomics and comfortability of the chair affects the process of writing the book. Essentially, ANT views processes of action and things that have an impact on the world as not merely the prerogative of humans, that non-human material objects also have an impact on how things unfold. ANT links closely to one of my main arguments throughout my thesis that materiality and discourse are connected, and that you cannot merely focus on one and ignore the other. In this way, ATFs would have agency now and in a nuclear future. Jasanoff and Kim's notion of "sociotechnical imaginaries" plays in extensively in this way, as it explores how imagined understandings of science and technology can lead to future scientific implementations in policy and development [189]. In terms of a theoretical framework for this thesis, my line of questioning lends itself to the ideas of Latour, Jasanoff, and Kim; however for the purposes of this thesis I will be relying less heavily on the theoretical framework of ANT. Although it would be interesting to take ANT further in this thesis, the emphasis of the interconnectedness of materiality and discourse when it comes to nuclear futures is sufficient to support my argument, with other aspects of ANT being out of scope for this work.

The development of nuclear futures will undoubtedly require technological innovation, but in order to explore nuclear futures, I must understand how the materialities of nuclear fuels and nuclear power in general interact with the social and the cultural in order to better anticipate socio-nuclear futures. In doing so, I argue that this will provide me further insight and a more comprehensive view into nuclear futures thinking, more so than an academic who sits in one discipline alone. This thesis takes seriously the call to no longer absolutely disconnect social sciences and humanities from material sciences. Throughout this thesis, I seek to realign disciplines that for far too long have artificially been kept apart. Foley, in his distinctions between the classical sciences and the humanities, claims that expanding collective knowledge is crucial when conducting research mostly for the classical sciences, and less so for the humanities [190]. Indeed, for many polarising issues in the humanities it is expected that a consensus is not able to be concluded, and therefore specificity has a prominent role in such research. Particularly where policy and governmental decisions are heavily involved with technological and societal progress, the humanities and classical sciences are inexorably intertwined in interdisciplinary research, which itself has intricacies in its combination of the disciplines.

Lélé and Norgaard discuss the complexities of carrying out interdisciplinary research, and highlight its barriers: individual value judgments in each stage of an inquiry; differing theories in response to the same phenomena; varying epistemological approaches; and the influence of society on conducting interdisciplinary research [191]. As a researcher who has primarily been trained in the classical sciences, I am habituated to its particular methodologies and interpretation of data. The generally objective approach is a component of the standards that provide rigour, and hence value, in classical science research. However, for qualitative research there exists contrasting views on the standardisation of practises, translating roughly into objectivity; Thøgersen argues that standardisation for complex models of language in interviews is unfeasible, and that the interpretation of social context, necessitating a degree of subjectivity, is salient to deriving meaning from such interactions [192]. Ratner elaborates on objectivism, which describes the reliance of subjectivity in objectivity: "objective knowledge requires active, sophisticated subjective processes" [193]. Realising that these complexities constituted the very nature of interdisciplinary research then equipped me with a recognition of my position as I navigated my research, with both subjectivity and objectivity defining my identity in my studies.

In this chapter, the methodologies in both the quantitative, material science approach as well as the qualitative, discursive approach in my research will be detailed to provide a substantial background to my outputs and conclusions. I have presented the methodologies here in the order of the content chapters proceeding from this current chapter.

2.1 Qualitative methods in participant research

In the material sciences, it is not a disciplinary necessity to dwell on the subjectivity of the researcher, or the values and perspectives they bring to their work. Carrying out research employing social sciences methodologies, on the other hand, necessitates an ongoing critical reflection on positionality due to the objects and subjects of social sciences research: human beings, their thoughts, feelings and world-views, within social, cultural and material networks. This process of considering positionality involves exploring the perspectives and values of the objects of the research, and the contexts in which they live, in order to better understand the possible motivations for what a participant might say or do. This applies equally to the researcher, who must look self-reflexively at their own perspectives and drives, which may influence the manner in which the research is undertaken [194, 195].

The positionality of a researcher is informed by many social aspects, identities and beliefs that encompass the relationships found and formed in a study. A researcher's reflexivity, therefore, provides a comprehensive evaluation of their positionality whilst acknowledging the standardised systems that the researcher and the research participants are subjected to [196]. There are also various nuances involved in researching; Merriam *et al.* writes of the complexities of 'insider' or 'outsider' status and of the shifting power dynamics when conducting research that aligns in many different dimensions to one's positionality [197]. Applying this framework to my research, my role as a contributor to the development of nuclear fuels affords me somewhat of an insider status to some of the sector employees, but concurrently transforms me into an outsider to some participants. It is reasonable for anti-nuclear campaigners to assume that as a computational nuclear materials scientist, I am an outsider relative to their cultural and historical actions and values, and that interactions in the interviews will be affected by my subjectivity. Similarly, for the sector employees, they are part of an industry where security and therefore confidentiality are key, and the risk of their words being misconstrued by an outsider may have played a role in their style of meticulous communication. For many researchers, they are simultaneously creators and consumers of knowledge, and they can influence and be influenced. In this interdisciplinary project, both of my research strands could have influence through their real-world applicabilities, which can therefore posit me as both an insider and an outsider in my interviews.

Michel Foucault writes extensively about the role that power relations play in an eclectic range of scenarios, distinguishing such relations from relationships of communication. Foucault considered power in many social and political contexts, such as in discourses surrounding sexuality as well as operations in prisons [198]. On power as an action, he remarks: “the exercise of power … is a way in which certain actions modify others” [199]. The Foucauldian approach to power is that of a structural theory, where a pervasive field of actions is imagined, and where movement is a predominant quality of power. In a resource-focussed system, Max Weber approaches power through a distributive lens, characterised in a zero-sum game: when two parties share a finite amount of power, a greater share of the power of one party decreases the remaining share of power of the other party [200, 201]. Weber also legitimises authority as “a special kind of power” [202]. Authority, in the context of nuclear power, occupies a constant presence, particularly where companies and governments can influence. Here, the distribution of power would become a major factor in the outcome of communicating advances in nuclear power. Theories such as those of Foucault and Weber attempt to detail the transfer and manifestations of power in society, which can comparably occur semantically in interviews and give a comprehensive understanding of the prevalence of power.

Feminist research has also provided much of the groundwork for exploring the notion of power in interviews. Extending this into the framework of intersectionality allows for critical analysis of social contexts in interviews and important discourse into futures thinking. Oakley discusses the objectification of interviewees in an interview setting and the paradigms that dictate the pseudo-conversation, as well as commenting on the polarities of “proper” and “improper” interviewing comparable to gender stereotyping in a patriarchal society; ultimately offering a reinterpretation of personal involvement in interviews that transcends bias and is instead an epitomisation of the social dynamics in everyday life [203]. Power dynamics are a salient component of interviews as they directly affect the data generated, and require some degree of emotional labour from the interviewer [204]. The power differential can be minimised by injecting the researcher's identity and character in the interview, releasing details about the researcher's rationale, and providing a full understanding of the research process [205]. The personalisation of the interview would then essentially impact the quality of the data from the interview.

The participants were made aware of my computational research into fuels for nuclear fission before their interviews, which will have prompted them to place me into various social categories. I am a young British-Chinese woman, and I speak articulate English with a Received Pronunciation accent, and so the implicit biases of the participants would have influenced their impression of me accordingly. These characteristics, coupled with my sartorial decisions and webcam placement in my home to display a particular setup, expressed a certain multimodality that would have affected the participants' subconscious attitudes towards me and conveyed various messages during the online interviews. For instance, using a plain background, dressing smartly, and using my Lancaster University Microsoft Teams account would have communicated to the participant that the interview is seen as being held in a professional institutional setting, thereby guiding the tone of the conversation. It should be noted that this attempt to research the impact of presentation on interview performance is held beyond the scope of the research. Elwood and Martin describe the interview location as a "'micro-geograph[y]' of spatial relations and meaning, where multiple scales of social relations intersect in the research interview" [206]. With the "location" being an online environment where interviewees can either opt to reveal their living arrangement or to use a virtual background or go without a webcam, it is a space where additional narratives can be explored inasmuch as they appear in the interactions of the participants with the digital platform itself and each other [207].

I chose to pursue mostly one-to-one semi-structured interviews because I was interested in learning how individual experiences shape the wider conversation around nuclear power, and how they can subsequently shape future conversations. Conducting the interviews first-hand allowed me to observe the subtleties in communication styles and prevalence of themes, and gain a more personal understanding of historical contexts through their lived experiences. For semi-standardised interviews, Flick elaborates on Scheele and Groeben's model of studying subjective theory; following the assumption that an interviewee holds extensive knowledge on a particular topic, they also are in possession of subjective theories on that topic [208, 209]. Making assumptions is a valuable part of the research process; however, Holmes warns against the misperception of research subjects by pigeonholing them based on the researcher's assumptions [195].

Purposive sampling was used to choose participants in order to obtain important viewpoints surrounding nuclear energy, whereby respondents are selected 'that are most likely to yield appropriate and useful information' [210, 211]. The criteria for this method of sampling sought to balance the views and experiences of the participants; they were contacted according to where they aligned themselves along the spectrum of opinion on nuclear power, which was mostly inferred from the organisations they were a part of, and made explicit in the interviews. I sought respondents with the intention of respecting their opinions, regardless of whether they differed from mine, as this is essential for forming futures, especially the one I present in Chapter 6. Nuclear fusion was also considered alongside nuclear fission; its role within the future energy landscape of the UK grew larger with substantial financial and support from the Government, with £220 million of funding going toward the Spherical Tokamak for Energy Production (STEP) programme, which aims to construct a prototype nuclear fusion plant by 2040 [212, 213]. With the anticipation of nuclear fusion having a greater mainstream presence in the coming years, and its unequivocal impact on communities, I strived to gain a wider perspective on the potential issues that a future society might face in exploiting energy generation from both nuclear fission and fusion. Additionally, I hoped to compare fission and fusion as a globally and commercially established technology and an increasingly researched technology with an inherited reputation, respectively. Hence, I also contacted organisations that were involved in the development of nuclear fusion, as well as its opposition. The processes of arranging the interviews and ethical approval are outlined in Appendix A.

The interviews were scheduled over a period of two weeks, from the 26th May to the 9th June 2021, according to the participants' availability. I interviewed eight representatives and members from organisations including: The UK Atomic Energy Authority (UKAEA); Together Against Sizewell C (TASC); Mothers for Nuclear; EDF Energy; Nuclear Legacy Advisory Forum (Nuleaf); Nuclear Free Local Authorities (NFLA); and Supporters of Nuclear Energy (SONE). Background information on these organisations and the participants can be found in Appendix B. Appendix C contains my interview aide-mémoire. It should be noted that this appendix does not list a question addressing ATFs explicitly for all interviews, as I wanted to understand perceptions towards nuclear technology developments in general that would include ATFs; although some interviewees had knowledge of ATFs and were happy to discuss them in the context of nuclear futures. Discourse analysis was applied to the transcriptions to obtain the summary of insights; the codes[1] used in undertaking the discourse analysis are outlined in Appendix D. This particular type of analysis focusses on the way language is inherently connected to social contexts, semiotics and narratives, encompassing various types of communicative systems. By tying together the discursive elements of the conversations, a more coherent dialogue will be achieved through multidimensional and multinarrative lenses, and the different facets of nuclear power that are produced will enable me to topographise the sentiments that surround it.

Lowes and Prowse discuss in detail the philosophical attributes present in phe-

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[1] In the social sciences, 'coding' is a technique of categorising data.

nomenology[2], with the focal points being Husserlian and Heideggerian phenomenologies applied to researchers and their preconceptions [215]. Husserl's method is centred around reductive knowledge, where researchers seek to remove or suppress layers of learned experiences for a deeper understanding of the lived experiences of others. This way, researchers operating under a Husserlian phenomenology would maintain an objective stance throughout their study [216]. Contrastingly, Heideggerian phenomenology is concerned with embodied knowledge that can only be understood through cultural and linguistic connections from living in a shared space, thereby requiring the researcher's experiences to be factored into the data [217]. In my interviews, adopting only a Husserlian phenomenology was difficult as I often found that I held contextual information that the interviewee did not, and my research was motivated by my personal connections to nuclear power as well as my preconceptions, thusly aligning my positionality in the interviews with varying levels of both Husserlian and Heideggerian phenomenology.

To challenge the preconceptions that shaped my positionality and power, it was important to reflect on my prior experiences with nuclear power. Growing up in the late 2000s and early 2010s, I viewed many defining moments in nuclear power such as the Three Mile Island and Chernobyl accidents (1979 and 1986, respectively) through a historic lens rather than as a once-current event. For the Fukushima Daiichi incident, I did not fully understand its significance at the time, and, similar to the other events, can only now study their aftermaths and ongoing consequences through documentation from others. This temporal distance, in addition to my embodied knowledge, choreographed my interview questions and positionality, and informed my connections with the participants through my own understanding of the social contexts that they associated themselves with. Furthermore, my preconceived beliefs surrounding nuclear power were largely influenced by social bias during my

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[2] Phenomenology is a theory in philosophical and social thought, which focusses on one's lived experience of the world [214]. In humanities research, phenomenology is particularly relevant when seeking to understand subjectivity and perceptions.

upbringing, during which I was exposed to less diversified views. Early influences included caregivers and my educational setting, and somewhat later on, social media. Often, views from these sources would acknowledge various issues of nuclear power, but did so in a way that maintained a certain narrative. For instance, in my undergraduate Physics degree, lectures on nuclear power would mention the concerns toward nuclear waste, simultaneously portraying it as a necessary evil since the main priority of the lecture was on progressing nuclear power technologies[3]. This is just one of many occurrences that contributed to my preconceptions and researcher bias in interviewing, and I was able to confront my subconscious attitudes in the interviews by inviting participants with a wide range of backgrounds. I noticed especially that I felt a substantial curiosity toward the participants who identified as opponents of nuclear power; this categorisation was again due to typifying myself—a researcher—as an outsider, thereby artificially amplifying my interest in such participants in an attempt to comprehend their lived experiences in order to carry out futures studies as a material-social scientist.

Here, I have considered my positionality as a result of differing identities in various contexts: a researcher; an interviewer; a student of a university, as both an insider and outsider. The singular element of positionality is important in exploring the power dynamics that arise from my positionality, and how they in turn influence the interactions with the participants. For a broader examination of the entanglements in a nuclear powered society, the participants and myself can all be thought of as actors with interpersonal connections in a shared world, living in different sociopolitical climates with unique environments. The positionality of “we” can also be essential in locating the contexts and frameworks that underpin our understanding of perspectives toward nuclear energy. The power in “we” lies in the cooperation and shared creation of the interview; there exists motives in participation to share expertise and motives in interviewing to extract important

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[3] Having carried out my doctoral research, upon reflection it would have been beneficial to add the fictional artefacts in Chapter 6 into the course material for these lectures to promote discussion.

information. This consequently increases the collective reservoir of knowledge with which nuclear futures can be explored further, and can be ultimately empowering for all who are involved in the interviews. Additionally, with power being the guiding force of policy and governmental decisions, these collaborations engender transgression and demonstrate the varying perceptions that are needed to enforce political, technical, material, ecological, psychological, and societal change. These interviews can provide a foundation for important insights into methods and approaches for interdisciplinary perspectives on nuclear powered futures for organisations seeking these changes, resulting in more considerate and outward-focussed implementations.

With the nuclear energy sector becoming increasingly enmeshed with other key groups in various energy and societal landscapes, the exploration of interpersonal relations that arise in developing technologies is imperative for charting its ramifications, as well as determining how it will be ingrained into the framework of society, enabling speculative futures to be designed in the process. This is particularly pertinent for the advancement and integration of ATFs and for the deployment of nuclear fusion reactors, as the intersections between materialities and societies are becoming increasingly prevalent. Hence, this research seeks to model how the nuclear sector must advance into the future if it plans for a successful distribution and commercialisation, as well as outline how it must move toward participatory research and engagement in the future in order to effectively communicate with a multitude of stakeholders. On the bridge between commercialisation and speculative insights, one of the arguments of this thesis is that so far, speculative insights are not currently being taken into consideration in the process of building nuclear futures, and this missing element is what facilitates the path of progression for nuclear power. Currently, research in the classical sciences often focusses solely on pushing technical boundaries without delving deep into the societal consequences. With as sensitive and contentious a technology as nuclear power, delving into the social consequences becomes increasingly important in a changing climate. For that, this thesis will provide a comprehensive and interdisciplinary insight into the relations of stakeholders and the nuclear sector in the UK, chiefly exploring inherent materialities arising from scientific advancements in the critical assessment of current narratives and discourse surrounding new nuclear technologies in order to reflect on the future of nuclear power.

2.2 Atomistic Simulation

When exploring ATFs as a possible route to safer nuclear futures, computational modelling is able to facilitate research and provide much insight into the behaviour and properties of these fuels. Computational predictions have taken place since the early stages of human development and primitive society, with one of the earliest predictive technologies considered to be the *Antikythera*, a grain calculator, dating back to ca. 80 B.C. [218, 219]. Nowadays, the advent of modern computers with an increased capacity for performing intensive tasks has allowed for the computational probing of the atomic makeup of materials at the nanoscale and beyond. Atomistic simulation methods have been rapidly developed through the years and adapted to modern systems, while still enabling quantitative predictions and new avenues of the physical world to be uncovered.

The characteristics of materials that are defined in atomistic simulations are underpinned by several sets of equations and theorisations that encapsulate real-world physics and work to describe the simulation system. The following sections will exhibit the theoretical underpinnings of atomistic simulation, as well as the mathematical descriptions of physical systems in the form of interatomic pair potentials.

2.2.1 Molecular Dynamics

The development of MD, which began in the 1950s, has enabled a vast number of interesting materials physics to be discovered. MD is an example of multiscale modelling, the paradigm of which allows for analysis on various temporal and spatial scales, as shown in Figure 2.1 [220]. The basis of MD lies in using Newton's classical laws of motion to evolve a system of atoms over time. For statistical physics simulation methods such as MD, the ergodic hypothesis is applied. This states that the statistical averages of a macroscopic property computed over long molecular timescales can be taken as equivalent to an experimental measurement [221]. The ability for large system investigations and the inclusion of external effects such as temperature and pressure in MD that are able to mimic experimental conditions has allowed for much insight into material behaviours. Indeed, in various academic disciplines, multiscale modelling has greatly benefitted from MD, ranging from probing dynamic protein structures [222] to building polymers in simulated chemical reactions [223].

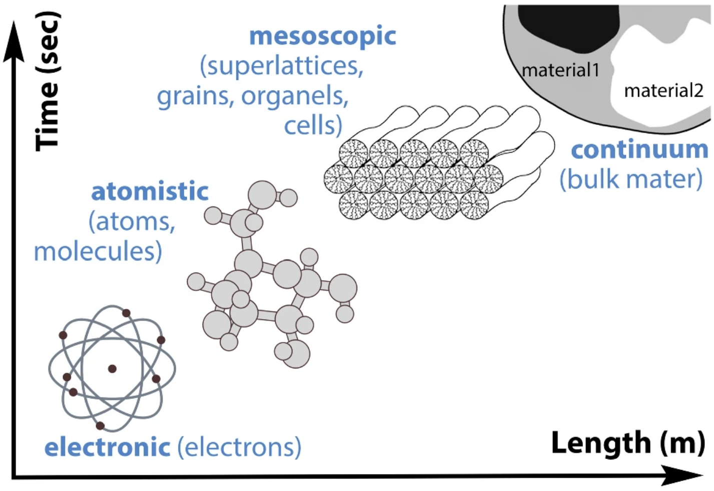


Figure 2.1: A diagram of the multiscale modelling paradigm, created by Verkovtsev, Solov'yov, and Solov'yov [220].

In simulating atomic structures, MD employs empirical pair potentials to provide the forces between each atom at various distances. The wide-ranging applications of MD have had real-world impacts and influences, and its versatility enables extensive insight into a myriad of materials. However, in solely utilising empirical pair potentials with Newtonian mechanics to simulate an atomic system, information on electronic bonding is contained in the empirical pair potential rather than managed explicitly, preventing investigations into charge transfer in materials. Owing to this limitation, MD has enabled simulations to be far less computationally expensive than other methods such as *ab initio* techniques, allowing for extensive system analysis in a variety of fields. Literally "from the beginning", multiscale *ab initio* techniques use approaches from first principles, meaning that only fundamental inputs are incorporated. In particular, DFT is an *ab initio* atomic-scale modelling approach that uses quantum mechanics to explore electronic structure of atoms in many-body systems. DFT aims to solve the Schrödinger equation to find the ground state for a system of particles. By solving the Schrödinger equation, these techniques provide a detailed understanding of the electronic structure in the material. It also allows for the inclusion of Hubbard values to modify the parameter space and allow for a better physical description of the atomic interactions [224]. By contrast, the classical MD approach subsumes information about the electronic bonding present in a material into an empirical pair potential. While this does reduce the model's ability to mimic processes involving charge transfer it is less computationally expensive and enables the simulations of materials at much greater time and length scales.

Equations of motion

To derive the equations of particle motion, we first consider a multi-particle system, made up of N particles [225]. The Hamiltonian of an N-particle system $H(\mathrm{p},\mathrm{r})$, which provides a description of the kinetic and potential energy of a system, can be represented using the inter-particle forces only:

$$H(\mathrm{p},\mathrm{r}) = H(\mathrm{p}_1,...\mathrm{p}_N,\mathrm{r}_1,...\mathrm{r}_N) = \sum_{i=1}^{N}\frac{\mathrm{p}_i^2}{2m_i} + U(\mathrm{r}_1,...\mathrm{r}_N) \tag{2.1}$$

where the positions and momenta of the particles are denoted by $(\mathrm{r}_1,...\mathrm{r}_N)$ and $(\mathrm{p}_1,...\mathrm{p}_N)$, respectively, m_i represents the particle masses, and $U(\mathrm{r}_1,...\mathrm{r}_N)$ is the potential energy experienced by the particles.

The derivative of the potential energy with respect to position can be calculated in order to obtain the forces on the particles, $\mathbf{F}_i$:

$$\mathbf{F}_i = -\frac{\partial U}{\partial \mathbf{r}_i} \tag{2.2}$$

Using Hamilton's equations, we begin to derive the equations of motion:

$$\dot{\mathbf{r}}_i = -\frac{\partial H}{\partial \mathbf{p}_i} \tag{2.3}$$

which gives:

$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i} = -\frac{\partial U}{\partial \mathbf{r}_i} = \mathrm{F}_i(\mathbf{r}_1, ...\mathbf{r}_N) \tag{2.4}$$

After substituting the derivative of equation 2.3 with respect to time into equation 2.4, we arrive at Newton's second law:

$$m_i\ddot{\mathbf{r}}_i = \mathbf{F}_i \tag{2.5}$$

thus describing the particle acceleration due to the force.

Integration algorithms

In order to evolve the system of atoms, Newton's equations of motion must be solved. However, for a system containing millions of atoms, calculating an exact solution is challenging. Instead, a numerical approach, in the form of an integration algorithm, is used to find an approximation to the solution. Integration algorithms advance the particle positions of an atomic system over a small time step, δt, from a time t. Integrators should be time-reversible and obey the laws of conservation for energy and momentum. They should also compromise well on computational cost, stability, and accuracy [226]; that is, there should be a reasonable trade-off between these factors. Verlet designed a simple method to integrate the equations of motion [227]. The particle positions can be ascertained from a Taylor expansion around a known point up to the second order term:

$$\mathbf{r}_i(t+\delta t) = \mathbf{r}_i(t) + \delta t \dot{\mathbf{r}}_i(t) + \frac{1}{2}\delta t^2 \ddot{\mathbf{r}}_i(t) + ... \tag{2.6}$$

The second and third terms in equation 2.6 contain descriptions of the velocity, $\mathbf{v}_i$, and acceleration, $\mathbf{a}_i$, respectively:

$$\mathbf{r}_i(t+\delta t) = \mathbf{r}_i(t) + \delta t \mathbf{v}_i(t) + \frac{1}{2}\delta t^2 \mathbf{a}_i(t) + ... \tag{2.7}$$

where $\mathbf{v}_i(t) = \dot{\mathbf{r}}_i(t)$ and $\mathbf{a}_i(t) = \ddot{\mathbf{r}}_i(t)$. Due to the equations of motion being time-reversible, it is possible to return to a previous time point using the same principle:

$$\mathbf{r}_i(t-\delta t) = \mathbf{r}_i(t) - \delta t \mathbf{v}_i(t) + \frac{1}{2}\delta t^2 \mathbf{a}_i(t) - ... \tag{2.8}$$

From adding equations 2.7 and 2.8, the velocities cancel such that the new positions can be calculated using the positions and accelerations at current and previous time steps:

$$\mathbf{r}_i(t+\delta t) = 2\mathbf{r}_i(t) - \mathbf{r}_i(t-\delta t) + \delta t^2 \mathbf{a}_i(t) \tag{2.9}$$

Then, the velocities of the atoms can be determined from:

$$\mathbf{v}_i(t) = \frac{\mathbf{r}_i(t+\delta t) - \mathbf{r}_i(t-\delta t)}{2\delta t} \tag{2.10}$$

Finding the velocities can be useful for calculating the kinetic energies of the atoms. However, this is problematic in the Verlet scheme because the positions at the next time step are required to be known, and the uncertainty on the velocities suffers from imprecision as they are greater than the uncertainty on the positions. To remedy this, a variation of the Verlet method—the leapfrog method—uses a half time step to calculate the velocities [228]:

$$\mathbf{v}_i\left(t + \frac{1}{2}\delta t\right) = \mathbf{v}_i\left(t - \frac{1}{2}\delta t\right) + \delta t \mathbf{a}_i(t) \tag{2.11}$$

By evaluating the velocities at $t + 1/2\delta t$, the positions can then be calculated at $t + \delta t$:

$$\mathbf{r}_i(t + \delta t) = \mathbf{r}_i(t) + \delta t \mathbf{v}_i \left(t + \frac{1}{2}\delta t \right) \tag{2.12}$$

Here, the positions and velocities leap over each other in sequence as the simulation progresses. However, this involves nonsynchronous calculations of the positions and velocities. Approximations for the velocities at time t can be used for the leapfrog method:

$$\mathbf{v}_i(t) = \frac{1}{2} \left(\mathbf{v}_i \left(t + \frac{1}{2}\delta t \right) + \mathbf{v}_i \left(t - \frac{1}{2}\delta t \right) \right) \tag{2.13}$$

The velocity Verlet algorithm developed by Swope *et al.* [229] overcomes the insufficiencies of both the Verlet and leapfrog methods. The velocity Verlet algorithm allows the position, velocity, and acceleration to be calculated at the exact time t. To obtain the velocity Verlet algorithm, we begin with a Taylor expansion for the velocity:

$$\mathbf{v}_i(t + \delta t) = \mathbf{v}_i(t) + \delta t \dot{\mathbf{v}}_i(t) + \frac{1}{2}\delta t^2 \ddot{\mathbf{v}}_i(t) + ... \tag{2.14}$$

Although the second term can be simplified using $\dot{\mathbf{v}}_i(t) = \mathbf{a}_i(t)$, the simplification of the third term is less trivial. Therefore, it undergoes a Taylor expansion up to the second order term:

$$\dot{\mathbf{v}}_i(t + \delta t) = \dot{\mathbf{v}}_i(t) + \delta t \ddot{\mathbf{v}}_i(t) \tag{2.15}$$

After multiplying equation 2.15 by $\delta t/2$ and rearranging, it becomes:

$$\frac{\delta t^2}{2} \ddot{\mathbf{v}}_i(t) = \frac{\delta t}{2} \dot{\mathbf{v}}_i(t + \delta t) - \frac{\delta t}{2} \dot{\mathbf{v}}_i(t) \tag{2.16}$$

and can be substituted into equation 2.14 to give:

$$\mathbf{v}_i(t + \delta t) = \mathbf{v}_i(t) + \delta t \dot{\mathbf{v}}_i(t) + \frac{\delta t}{2} \dot{\mathbf{v}}_i(t + \delta t) - \frac{\delta t}{2} \dot{\mathbf{v}}_i(t) \tag{2.17}$$

After simplifying further, we arrive at:

$$\mathbf{v}_i(t+\delta t) = \mathbf{v}_i(t) + \frac{\delta t}{2}\left(\mathbf{a}_i(t+\delta t) + \mathbf{a}_i(t)\right) \tag{2.18}$$

which, along with equation 2.7, constitute the velocity Verlet integration algorithm. The algorithm works in a number of stages, with the initial stage involving the evaluation of updated positions using equation 2.7. Then, half time steps are used to calculate the velocities using:

$$\mathbf{v}_i\left(t+\frac{\delta t}{2}\right) = \mathbf{v}_i(t) + \frac{\delta t}{2}\mathbf{a}_i(t) \tag{2.19}$$

An empirical pair potential is used to provide the forces experienced between the atoms, which enables the calculation of the accelerations using equation 2.5. Finally, the updated velocity can be calculated using:

$$\mathbf{v}_i(t+\delta t) = \mathbf{v}_i\left(t+\frac{\delta t}{2}\right) + \frac{\delta t}{2}\mathbf{a}_i\left(t+\frac{\delta t}{2}\right) \tag{2.20}$$

The velocity Verlet algorithm is the most widely incorporated integrator in MD simulations [230]. The manipulation of the time step, δt, throughout the algorithm plays an essential role in determining the kinetic properties of the atoms. It is equally essential to consider the time step itself in performing MD simulations; the length of δt should be large enough for the quick sampling of phase spaces, which lessens the computational cost, whilst being small enough to avoid large truncation errors in the integration calculations [231]. Typically, this balance is achieved in MD simulations by using time steps that are < 2 fs [232]. For the purposes of this work, a time step of 1 fs is used throughout the MD simulations.

Ensembles

In a system of N particles, where N is conserved, there are different thermodynamic ensembles that the system can exist in. The descriptors of these conditions are called ensembles, and they can influence changes in atomic behaviour, which affects the resulting kinetic and potential energies of the system, shown in equations 2.21 and 2.22, respectively:

$$K = \frac{1}{2}\sum_{i=1}^{N} m_i v_i^2 \tag{2.21}$$

$$U = \frac{1}{2}\sum_{i=1}^{N} U_i \tag{2.22}$$

If the volume, V, is fixed in a system, and the forces experienced by the atoms are exclusively representative of the potential energy, the system is in a microcanonical (NVE) ensemble, where the total energy of the system, E, is constant:

$$E = K + U \tag{2.23}$$

Although E is conserved, K and U are subject to fluctuations in the simulation, and as a consequence, the temperature is free to change, approximated by:

$$T(t) = \frac{m}{3Nk_\mathrm{B}}\sum_i v_i^2 \tag{2.24}$$

where k_B is the Boltzmann constant. However, in purposing the simulations to replicate experimental conditions, it is essential to regulate the temperature. The canonical (NVT) ensemble allows for the temperature to be controlled using a thermostat. Various thermostats have been developed for this, including the Berendsen thermostat [233], Andersen thermostat [234], and the Nosé-Hoover thermostat [235–237]. In particular, the Nosé-Hoover thermostat incorporates a fictitious degree of freedom, s, in the energy in order to introduce a heat bath into the system that provides energy. The kinetic and potential energies of s are then given by equations 2.25 and 2.26, respectively:

$$K(s) = \frac{Q(ds/dt)^2}{2} \tag{2.25}$$

$$U(s) = (3N+1)k_B T \ln s \tag{2.26}$$

where $(3N+1)$ denotes the number of degrees of freedom, and Q is a fictitious mass for s. In connecting the heat bath to a real system, we create an extended system that we assume to be microcanonical. Then, the real system is in a canonical ensemble, with the coupling strength between the heat bath and the real system dictated by Q. In simulations, thermostatting requires a damping parameter to allow the temperature of the system to relax. For an isobaric-isothermal (NPT) ensemble, a barostat is used in addition to a thermostat, with its own damping parameter. In MD, a barostat adjusts the simulation box dimenstions to apply a certain pressure to the system [238].

Creating an MD simulation

MD simulations present an opportunity to accurately represent the larger structures present in the material. Therefore, the unit cell can be duplicated to form a larger body of atoms called a supercell. Molecular dynamics can make use of periodic boundary conditions, shown in Figure 2.2, which can be applied to a supercell to replicate an infinitely large lattice. Under periodic boundary conditions, an atom that travels over the boundary and out of the cell box would reappear and enter at the other side of the box, retaining its same velocity.

The velocities of the atoms are such that they correspond to the temperature of the system, whilst ensuring that the conservation of momentum is obeyed. The velocities can be produced using a Maxwell-Boltzmann distribution:

$$f(v_i) = \sqrt{\frac{m_i}{2\pi k_B T}} \exp\left(\frac{-m_i v_i^2}{2k_B T}\right). \tag{2.27}$$

Throughout this work, MD simulations were performed using the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) [239], with the structure file of UN provided in the form of a Crystallographic Information File (entry 4124680) from the Crystallography Open Database (COD) [240, 241]. Atomsk [242] was used to create supercells and perform lattice manipulation, and the Open Visualization Tool (OVITO) [243] was used to analyse atom trajectories and produce visuals.

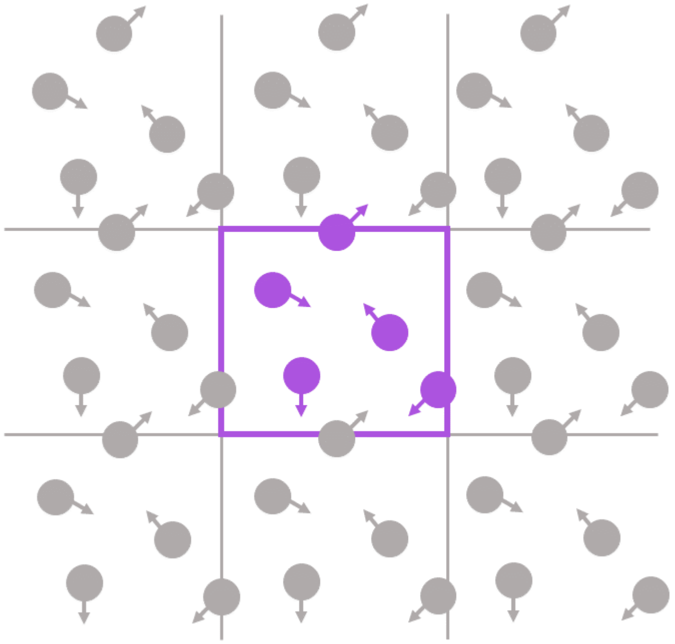


Figure 2.2: A diagram illustrating periodic boundary conditions in two dimensions. The purple box and atoms represent the simulation cell, and the grey atoms and lines represent the periodic images.

2.2.2 Interatomic potentials

In an MD simulation, the forces that interacting objects experience are required to be able to evaluate the equations of motion and progress the simulation, as detailed in section 2.2.1. Interatomic potentials, also known as empirical pair potentials, are a way to calculate the forces between atoms i and j with a defined separation distance r_{ij} to the simulation. In this section, I will detail some empirical relations that can describe the interactions between atoms.

Embedded-atom method

The embedded-atom method (EAM) is a model that describes metal and metal alloy systems [244–248]. In such systems, the ions are surrounded in a 'sea' of delocalised electrons that are not bonded to any specific ion. The interactions between the electrons and ions in the metal give rise to the bonding in the metal, which the EAM attempts to describe. This differs from ionic crystal systems, where only the interaction energies between atoms inform their total potential energy. In the EAM model, the ions are understood to be embedded in a charge density that arises due to the other ions in the system. The total energy for a system of N atoms can be written as a sum of the individual atomic energies [249]:

$$E_{tot} = \sum_{i}^{N} E_i \tag{2.28}$$

Then, the EAM potential takes the form of:

$$E_i = F(\bar{\rho}_i) + \frac{1}{2}\sum_{j\neq i} \phi(r_{ij}) \tag{2.29}$$

where $\phi(r_{ij})$ is the pairwise interaction between atoms, and $F(\bar{\rho}_i)$ is the embedding function due to the ion i being embedded within the total electron density, $\bar{\rho}_i$ [250]:

$$\bar{\rho}_i = \sum_{j\neq i} \rho(r_{ij}) \tag{2.30}$$

The pairwise interaction term in the EAM potential, $\phi(r_{ij})$, represents the repulsion between nuclei and so the embedding term effectively represents the energy benefit from placing a nucleus in a ‘sea’ of electrons.

Angular-dependent potential

The Angular-Dependent Potential (ADP), developed by Mishin, Mehl, and Papaconstantopoulos [251], is a generalisation of the EAM, designed to account for covalent bonding in atomic systems. Defined in a Cartesian system, the total potential energy is composed of 5 terms:

$$E = \frac{1}{2}\sum_{i,j(j\neq i)} \phi_{mn}(r_{ij}) + \sum_{i} F_m(\bar{\rho}_i) + \frac{1}{2}\sum_{i,\alpha}(\mu_i^{\alpha})^2 + \frac{1}{2}\sum_{i,\alpha,\beta}(\lambda_i^{\alpha\beta})^2 - \frac{1}{6}\sum_{i}\nu_i^2 \tag{2.31}$$

where $\alpha, \beta = 1, 2, 3$ denote the directions in the Cartesian system, and m and n represent the element types. The first and second terms are similar to the EAM model, respectively providing the pair potential between atoms i and j, and the embedding function. These first two terms are not dependent upon the bond angles in the system, but the final three contain angular terms that penalise energy deviations from cubic symmetry. The third and fourth terms provide the dipole and quadrupole distortions around atom i in vector and tensor form, respectively:

$$\mu_i^{\alpha} = \sum_{j \neq i} u_{mn}(r_{ij}) r_{ij}^{\alpha} \tag{2.32}$$

$$\lambda_i^{\alpha\beta} = \sum_{j \neq i} w_{mn}(r_{ij}) r_{ij}^{\alpha} r_{ij}^{\beta} \tag{2.33}$$

where u and w are extra pairwise functions. The fifth term is the trace of the tensor in equation 2.33:

$$\nu_i = \sum_{\alpha} \lambda_i^{\alpha\alpha} \tag{2.34}$$

In this work, an ADP potential for UN was used to provide the forces in the UN lattice, with the specific parameterisation developed by Tseplyaev and Starikov [252]. The energy as a function of r_{ij} is shown in Figure 2.3 for this potential.

The Buckingham potential

The Buckingham potential is often used with Coulomb's law to describe molecular systems. Dependent only upon pairwise interactions, the form of the Buckingham potential is:

$$E_{Buck} = A_{ij} \exp\left(\frac{-r_{ij}}{\rho_{ij}}\right) - \frac{C_{ij}}{r_{ij}^6} \tag{2.35}$$

where A_{ij} and ρ_{ij} are parameterisations of the short-range repulsive forces arising due to the Pauli exclusion principle, and C_{ij} characterises the attractive van der Waals' and London dispersion forces [253]. When $r_{ij} \to 0$, the $1/r_{ij}^6$ dominates, and $E_{Buck} \to -\infty$. Physically, this translates into the atoms collapsing onto each other. This is known as the "Buckingham Catastrophe" [254, 255].

In UO_2, Cooper *et al.* used a Buckingham potential to describe the Xe-U and

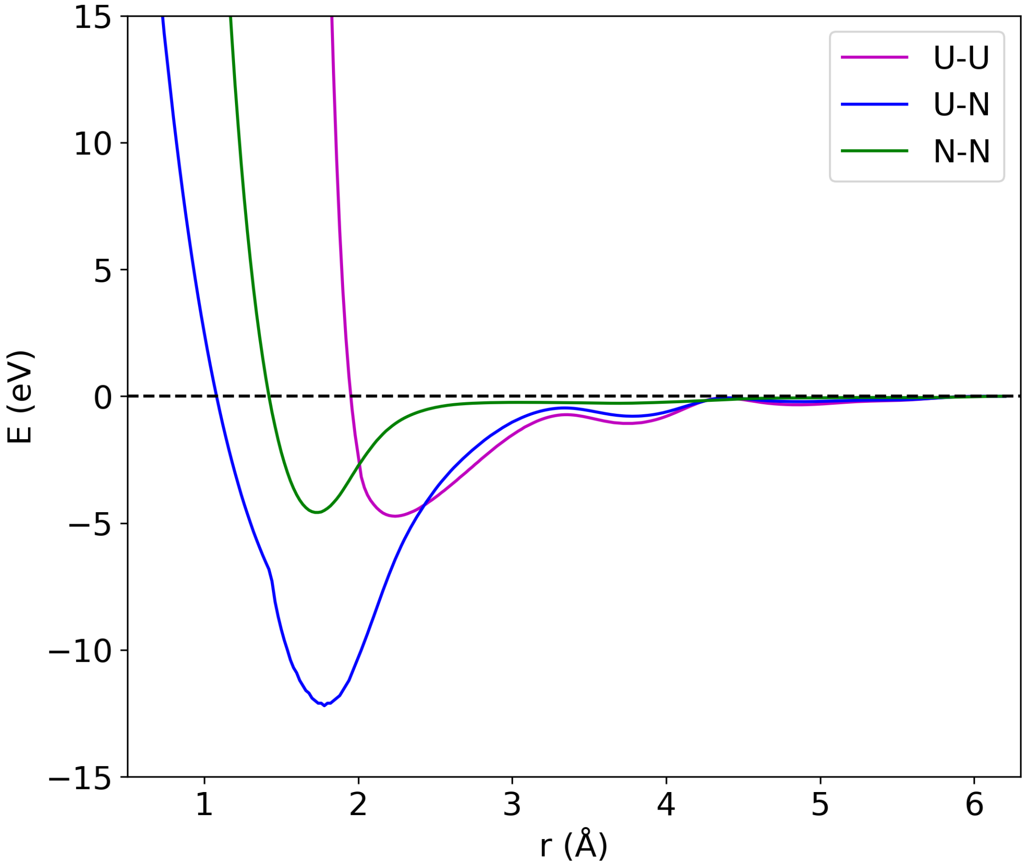


Figure 2.3: A graphical representation of the ADP for UN developed by Tseplyaev and Starikov [252].

Xe-O interactions in a Xe-UO_2 system [256–259]. Their choice of a Buckingham potential stemmed from Xe being an inert gas, so the entirely pairwise Buckingham potential was sufficient to describe the interactions for Xe-UO_2. Energies for the Xe-Xe interactions were provided in a tabulated form of the Tang and Toennies gas-gas potential [260], as seen in Figure 2.5. The Xe-U and Xe-O Buckingham potential values from Cooper *et al.* are shown in Table 2.1, and the graphical representations of the energy as a function of r_{ij} for this potential are shown in Figure 2.4.

Pair	$\boldsymbol{A}$ **(eV)**	$\boldsymbol{\rho}$ **(Å)**	$\boldsymbol{C}$ **(eV· Å^6)**
Xe-U	6606.398	0.298	19.013
Xe-O	1877.599	0.340	46.478

Table 2.1: The Buckingham potential values for the Xe-U and Xe-O interactions, developed by Cooper *et al.* [256].

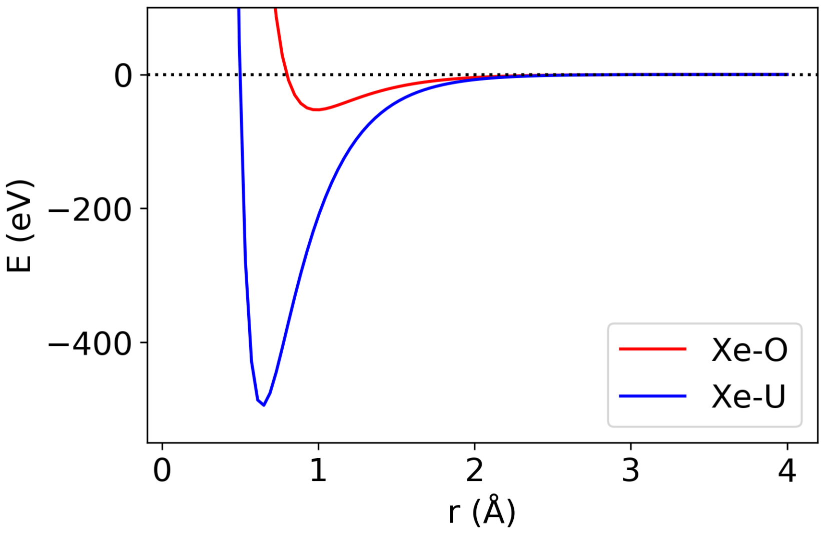


Figure 2.4: A graphical representation of the energy as a function of r_{ij} in the Xe-O and Xe-U Buckingham potentials developed by Cooper *et al.* [256].

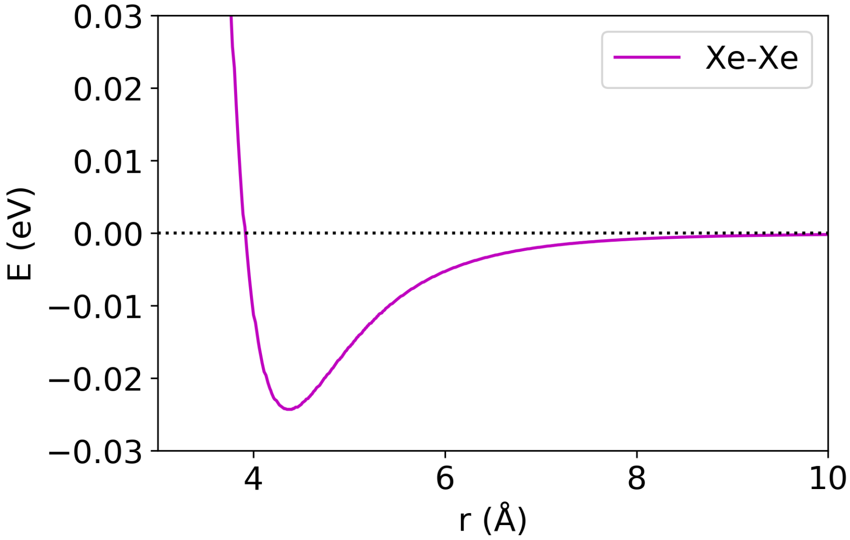


Figure 2.5: A graphical representation of the energy as a function of r_{ij} in the Xe-Xe potential from the Tang and Toennies set of fission gas potentials [260].

2.3 Atomic behaviour

As described in section 1.1.2, the presence of defects within an atomic lattice can alter a material's properties and dynamic lattice behaviour. In order to understand the physical underpinnings of defect creation and lattice movements, their theoretical descriptions will be detailed in the next few sections.

2.3.1 Defects in materials

According to the second law of thermodynamics, any crystal at thermodynamic equilibrium must have some degree of entropic disorder, materialising in the form of defects [261]. Defects are categorised according to their dimensionality. Point defects are zero-dimensional, contrasting with one-dimensional line dislocations, two-dimensional loop dislocations, or three-dimensional volume defects in the form of bubbles [262]. Point defects can be categorised further into intrinsic vacancies, interstitials, and antisites that belong to the host supercell, and extrinsic impurity atoms that are of a different species than that of the host supercell, occupying substitutional or interstitial positions [263]. Specific intrinsic defects, like the thermally activated Frenkel and Schottky defects, are shown in Figure 2.6 for a simple binary crystal lattice, alongside a depiction of an antisite pair defect. A Frenkel process is one where an atom is displaced into an interstitial site, creating a vacancy and an interstitial, and a Schottky process is one where vacancies are created, and the ion that has been displaced goes on to form new material. Antisite defects are atoms on non-native sites.

Thermodynamics of point defects

As the temperature of a material is increased, the atoms within possess more thermal energy to move from their sites into defect positions. The increased thermal creation of defects leads to an increased number of possible defect arrangements; this in turn increases the entropy of the system. To investigate this further, we firstly consider a lattice held at constant temperature and pressure to be able to inspect the change in the Gibbs free energy, ΔG:

$$\Delta G = \Delta U - p\Delta V - T\Delta S \tag{2.36}$$

where p denotes pressure, ΔU is the change in the internal energy of the lattice, ΔV is the change in its volume, and ΔS is its change in entropy. The second term

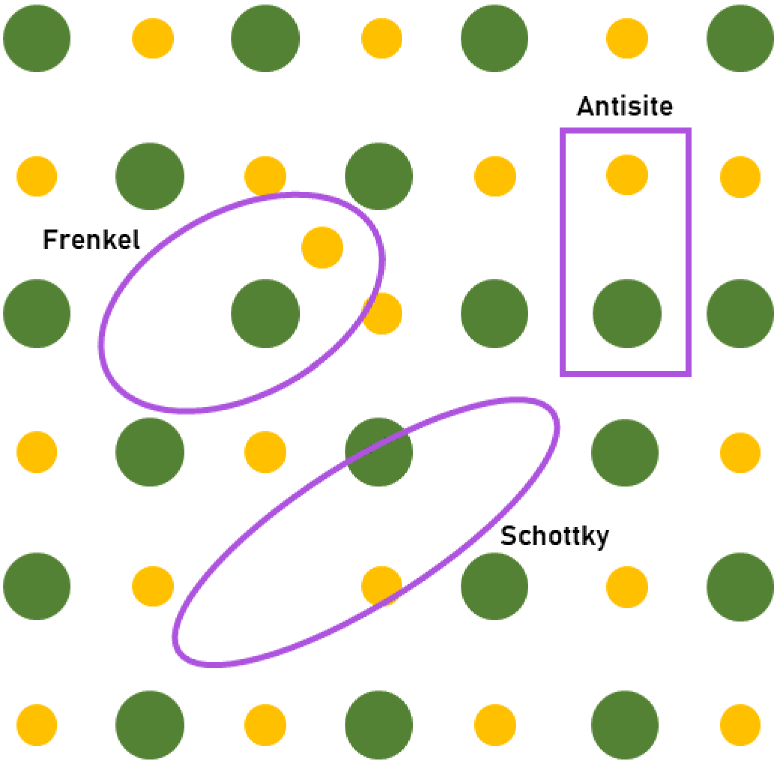


Figure 2.6: A diagram showing local examples of Frenkel, Schottky, and antisite pair defects in a binary crystal lattice.

is taken as zero as ΔV becomes negligible for constant p and T. Now, if E_f is the amount of energy required to form a defect, and there are n defects, then the change in the internal energy of the system due to incorporating the defects can be written as the product between the two terms [264]:

$$\Delta U = n\Delta E_\mathrm{f} \tag{2.37}$$

The entropic increase of the system arising from this process can be determined from the Boltzmann formula [265]:

$$\Delta S = k_\mathrm{B} \ln W \tag{2.38}$$

where W are the defect microstates of the system, which are the number of ways that defects can be arranged. In a system of anion and cations, the anion microstate, W_anion, can be found for n anion vacancies and N anion sites:

$$W_\mathrm{anion} = \frac{N!}{n!(N-n)!} \tag{2.39}$$

A similar expression can be obtained for W_cation using equation 2.39, and when placed into equation 2.38, gives:

$$\begin{align} \Delta S &= k_\mathrm{B} \ln W_\mathrm{anion} W_\mathrm{cation} \tag{2.40}\\ &= k_\mathrm{B} \ln \left(\frac{N!}{n!(N-n)!} \frac{N!}{n!(N-n)!} \right) \tag{2.41}\\ &= 2k_\mathrm{B} \left(\ln(N!) - \ln(n!) - \ln(N-n)! \right) \tag{2.42} \end{align}$$

For large n, the Stirling approximation can be used [266], where $\ln(n!) \approx n \ln n$. This then transforms equation 2.42:

$$\Delta S = 2k_\mathrm{B} \left(N \ln N - n \ln n - (N-n) \ln(N-n) \right) \tag{2.43}$$

and when equations 2.43 and 2.37 are inserted into equation 2.36, we obtain:

$$\Delta G = n \Delta E_\mathrm{f} - 2k_\mathrm{B} T \left(N \ln N - n \ln n - (N-n) \ln(N-n) \right) \tag{2.44}$$

If we consider the system to be at thermodynamic equilibrium, then the Gibbs free energy is at a minimum with respect to n:

$$\frac{\partial \Delta G}{\partial n} = \Delta E_\mathrm{f} - 2k_\mathrm{B} T \ln \left(\frac{N-n}{n} \right) = 0 \tag{2.45}$$

and by assuming that there are many more lattice sites than defects, we can approximate the number of defects to be negligible, and apply $N \gg n$ such that $(N - n) = N$. Then, after some rearranging and inverting, we arrive at:

$$c = \exp\left(-\frac{\Delta E_\mathrm{f}}{2k_\mathrm{B}T}\right) \tag{2.46}$$

where $c = n/N$ is the concentration of point defects. Equation 2.46 describes how the concentration of point defects is related to the energy required to form the defect. The formation energy for a defect from a DFT simulation can be determined from:

$$\Delta E_\mathrm{f} = E_\mathrm{def} - E_\mathrm{perf} \pm \sum_i n_i \nu_i \tag{2.47}$$

where E_def represents the energy of the system containing defects, E_perf is the energy of the defect-free system, n_i is the number of atoms of type i added or removed and ν_i is the chemical potential of i. For U and N, the chemical potential can be expressed as:

$$\nu_{UN}\left(\rho_{N_2}, T\right) = \nu_N\left(\rho_{N_2}, T\right) + \nu_U\left(\rho_{N_2}, T\right) \tag{2.48}$$

where $\nu_{UN}\left(\rho_{N_2}, T\right)$, $\nu_N\left(\rho_{N_2}, T\right)$ and $\nu_U\left(\rho_{N_2}, T\right)$ are the chemical potentials of UN, N, and U respectively, which are all dependent upon both the temperature and the partial pressure of N_2.

Finally, the incorporation energy of an extrinsic fission gas atom (FGA) onto a pre-existing defect site is defined in Equation 2.49,

$$E_\mathrm{inc} = E_\mathrm{def}(\mathrm{FGA}_\mathrm{trap}) - E_\mathrm{def}(V_\mathrm{trap}) \tag{2.49}$$

where $E_\mathrm{def}(\mathrm{FGA}_\mathrm{trap})$ is the energy of a defect with an external FGA occupying the defect trap, and $E_\mathrm{def}(V_\mathrm{trap})$ is the energy of a defect prior to the FGA occupying the trap site [267].

For the concise description of defect processes, Kröger–Vink notation has been used in this work [268]. For example, in this notation $\mathrm{Xe_N}$ denotes a xenon atom on a nitrogen site. Additionally, V and i denote vacancies and interstitials where written; V_N and Xe_i represent a nitrogen vacancy and a xenon interstitial, respectively.

The migration energy, E_m, is the difference in energy between the minimum and maximum energies in a defect's migration pathway, and is illustrated in Figure 2.7 [269, 270].

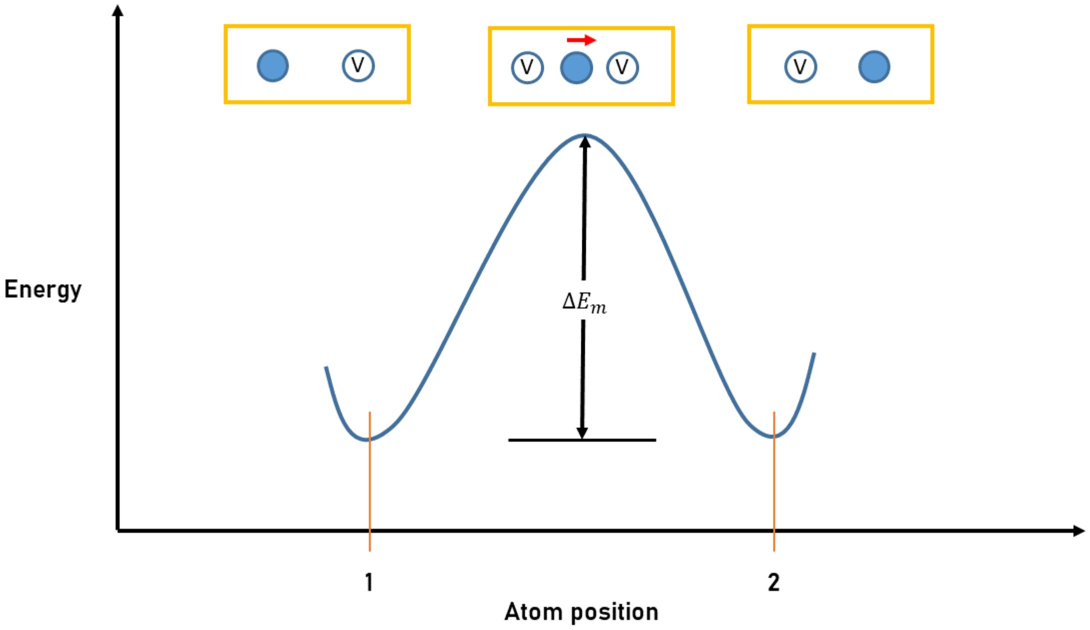


Figure 2.7: A visualisation of the migration energy barrier using an example of a migrating vacancy [269]. In moving from position 1 to position 2, the atom experiences a migration energy barrier; ΔE_m is the change in energy required to overcome this barrier.

2.3.2 Atomic diffusion

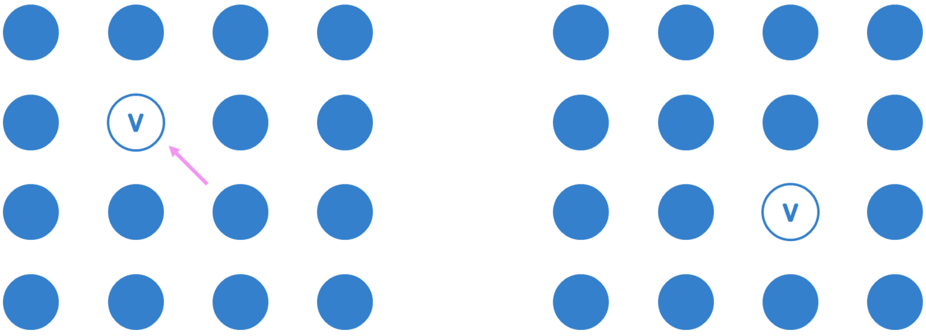
Diffusion is a process that allows material transport through an atomic lattice, and is described using Fick's law, which states that the rate of diffusion across a unit area is proportional to a non-uniform gradient [262, 271, 272]:

$$J = -D\frac{\partial C}{\partial x} \tag{2.50}$$

where J is the atomic flux, D is the diffusion coefficient, and $\frac{\partial C}{\partial x}$ is the concentration gradient. For diffusion to occur, an atom needs to overcome its migration barrier, the energy required to break the bonds with its neighbours. The diffusion of defects in the lattice, characterised by their activation energy, E_a, can then be described using E_f and E_m:

$$E_\mathrm{a} = E_\mathrm{f} + E_\mathrm{m}. \tag{2.51}$$

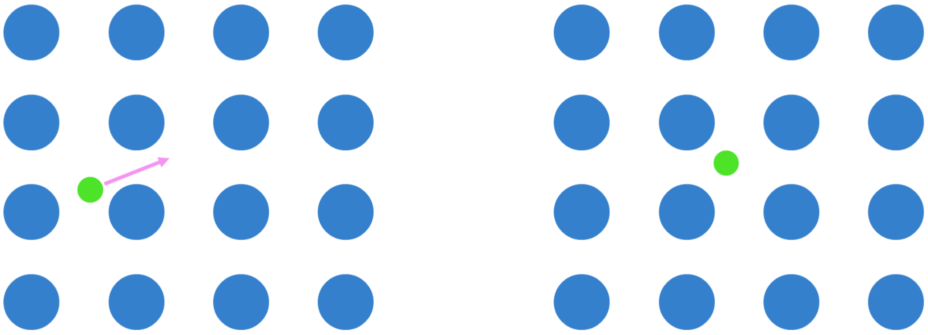
For a metal, there are two main diffusion mechanisms: vacancy diffusion and interstitial diffusion [272]. Vacancy diffusion, which is illustrated in Figure 2.8, requires there to be a pre-existing neighbouring vacant site. For interstitial diffusion, which is shown in Figure 2.9, an interstitial atom moves from one interstitial position to another within the lattice.



(a) (b)

Figure 2.8: The vacancy diffusion mechanism, shown in a lattice system. An atom moves along the pink arrow to the vacant position, denoted by the circled ‘V’ in 2.8a. In 2.8b, the site that the atom leaves is now a vacant site.

In a solid, diffusion is instigated by the thermal hopping of atoms between sites, and is driven by either a thermal or concentration gradient. To evaluate the mobility



(a) (b)

Figure 2.9: The interstitial diffusion mechanism, shown in a latticial system. In 2.9a, the green interstitial atom atom moves along the pink arrow to its new interstitial position, as shown in 2.9b.

of atoms in the lattice, the mean squared displacement (MSD) can be calculated. The MSD, which is derived from Brownian motion [273], is calculated as the average displacement of an atom from its initial position over a squared time interval. The diffusivity, D, is related to the MSD through:

$$\mathrm{MSD} = 2nDt, \tag{2.52}$$

where n represents the dimensionality of the system. As the UN matrix in this work is three dimensional, $n = 3$ in this case. From calculating D at various temperatures, T, and plotting as a function of $1/T$ to create an Arrhenius plot, it is possible to extract the activation energy, E_a, and the diffusion coefficient, D_0, from:

$$D = D_0 \exp\left(\frac{-E_a}{k_B T}\right), \tag{2.53}$$

and provide a greater amount of detail into defect behaviours in the lattice. It should be noted that E_a is for when defects are not already included; if defects are present, energy will not need to be spent to create defects, and therefore E_a drops to E_m. It is important to note that the computational simulations performed in this thesis are energy only analyses, as they only indicate the ease with which the atoms can diffuse as there is no driving force. Essentially, the simulations in this thesis provide information on how easy it is for certain atoms to diffuse through a lattice.

2.4 Futures methods

As both a research and a practice, modern futures thinking methods have built on philosophical and social schools of thought emerging in the mid-Twentieth Century, as well as the tools of post-World War II statistical analysis and military planning, and allow for a wide application in a variety of fields. Some of these methods are outlined in Figure 2.10, adapted from Sharpe *et al.* [274], who explain how futures practices use present decisions to incorporate uncertainty into futures outcomes. They emphasise that some methods can also work well in certain situations that belong to a different quadrant; for example, using a pathways approach in a low uncertainty, high agency context begins to transform it into a roadmapping method. In this way, there remains the ability to act on futures strategies, only it is concentrated in one pathway.

Ogilvy's axes of uncertainty is a method that uses scenarios to configure futures journeys [275]. The axes of uncertainty—as shown in Figure 2.11—uses a two-dimensional matrix to outline scenarios according to extremes in the uncertainty of two sets of drivers.

On scenarios[4], Curry critically outlines their benefits and limitations, giving an account of their emergence and history [276]. Scenarios first appeared after World War II, emerging as two branches of scenarios. The first branch was concerned with military planning, where scientific and technical knowledge was used in scenarios that informed strategies. The second branch appeared in the spirit of "post-war reconstruction", and was centred around narratives and imaging the future[5] [277].

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[4] Here, a scenario is defined as a descriptive potential future, that can help to inform the pathway to that future.

[5] Polak's main argument in *The Image of the Future* is based around the idea that the projections

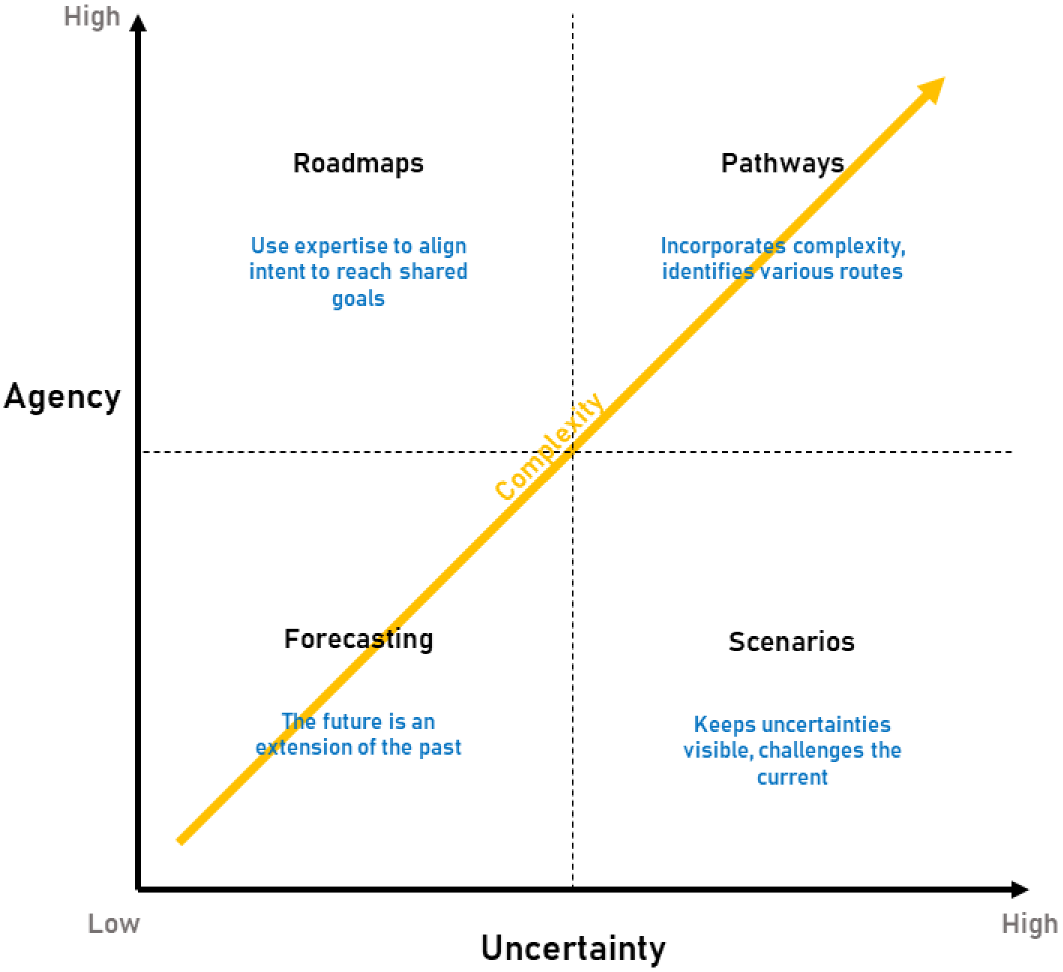

Figure 2.10: An illustrative description of four major futures thinking tools, placed in each quadrant according to their usefulness for different levels of agency and uncertainty. Adapted from Sharpe *et al.* [274].

Slaughter [278] further defines these two scenarios branches as “problem-oriented futures” and “critical and epistemological futures”, respectively. As a futures practice, scenarios became embedded into methodological repertoires in the 1970s, and as shown in the axes of uncertainty in Figure 2.11, are an integral part of realising and commencing futures. Rowland and Spaniol characterises scenarios using six classifications: they are orientated towards the future; focus on the external environment; are described narratively; are plausible; are a “systematised set”; and are different to

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of the future inform our perspective of it, and in turn, our ability to influence the images of the future [277].

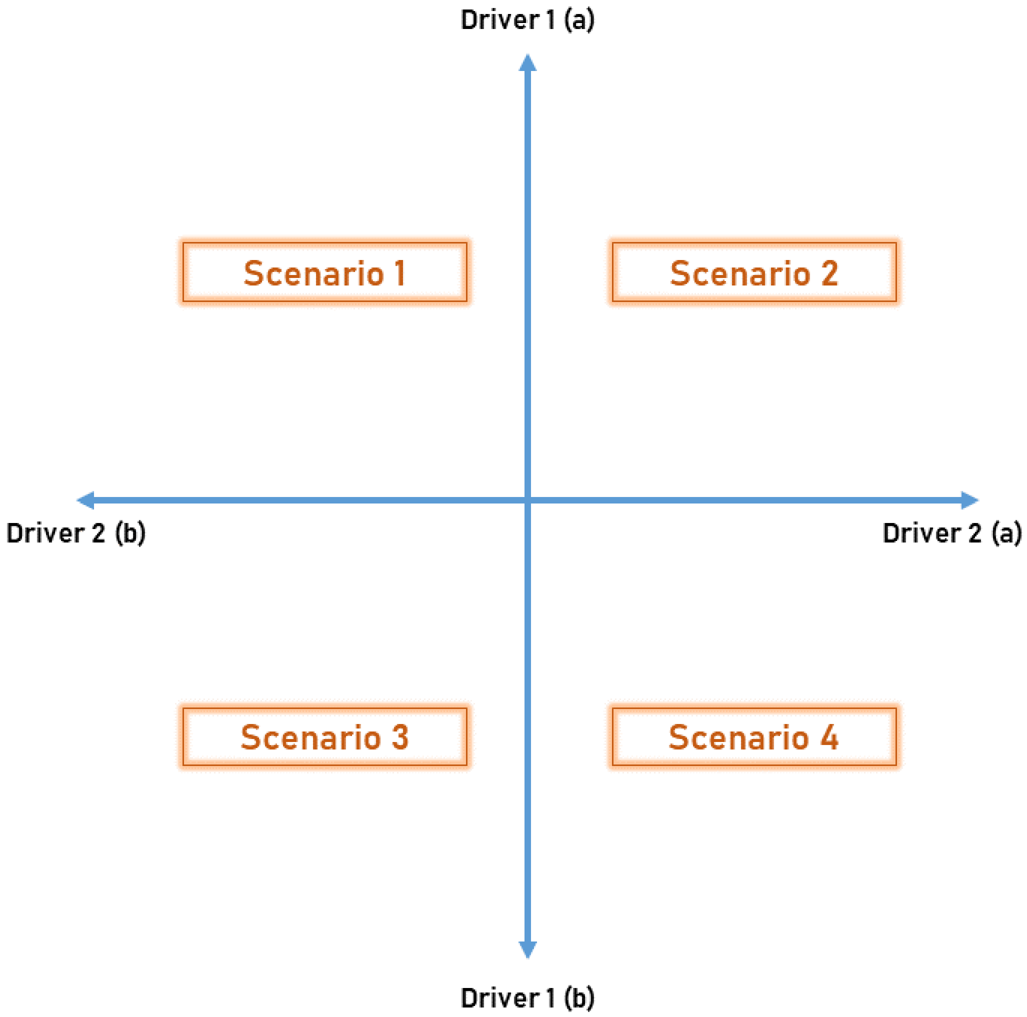

Figure 2.11: The axes of uncertainty. In this method, two levels of uncertainty attached to each driver are used at the extremes of each axis of the matrix, denoted by (a) and (b). The four scenarios then arise from the combination of two drivers at different levels of uncertainty.

each other [276, 279]. However, the axes of uncertainty and axes-specific scenarios can tend to propagate the “business as usual” idea, and leave little room for implausible futures. Despite this, scenarios can provide a useful way of visioning futures; scenarios exercises provide a storied aspect to futures [280]. There is still much to be uncovered in the theorisation and ontological research of scenarios that could potentially lead to an increased uptake in scenarios planning in less hegemonic spaces. To accommodate scenarios in futures work, they work in harmony with a multitude of other methods through incorporating them in a series of stages to produce useful and robust possible futures.

In their research, Sharpe *et al.* notice how researchers gravitate towards epistemic forms of knowledge, where "teachable" knowledge is used to create value and inform rules. However, they reason that "epistemic knowledge alone cannot facilitate the kinds of change needed to address contemporary societal challenges", and so in endeavouring to engage people to "take responsibility" for their roles in creating futures, demonstrated a less epistemic approach to futures thinking: the Three Horizons method [274]. The Three Horizons practice builds on the pre-existing practice of Horizon Scanning, which is one of the most widely used methods, with practitioners ranging from policymakers in the UK government [281] to software companies [282]. First introduced by Baghai, Coley, and White [283], the Three Horizons method—shown in Figure 2.12—takes into account the transformative and causational impacts that decisions produce, and foregrounds the transfer of power in FL [274]. This approach takes the form of three horizons: **H1**, **H2**, and **H3**. The first horizon, **H1**, represents a business-as-usual case, where emerging conditions cause the current system to no longer be suitable for continuation. A "realm of transition" in the form of **H2** brings forward turbulent disruptions, where innovative changes can either fail and become subsumed into **H1**, or facilitate the upsurgence of **H3**. This third horizon characterises an emergent successive pattern that is "on the fringes of the present system" [274], and registers new realities originating from implementing the innovations in **H2**. The Three Horizons approach is iterative; as time progresses, new systems of **H1**, **H2**, and **H3** will appear, on the predication of there being continual change and progress. The Three Horizons approach is commonly used to develop and change scenarios, which allows for emphasis on transitory implementations in futures thinking methods.

In Dator's 2009 essay *Alternative Futures at the Manoa School* [284], he outlines the futures visioning process used by the Hawai‘i Research Center for Futures Stud-

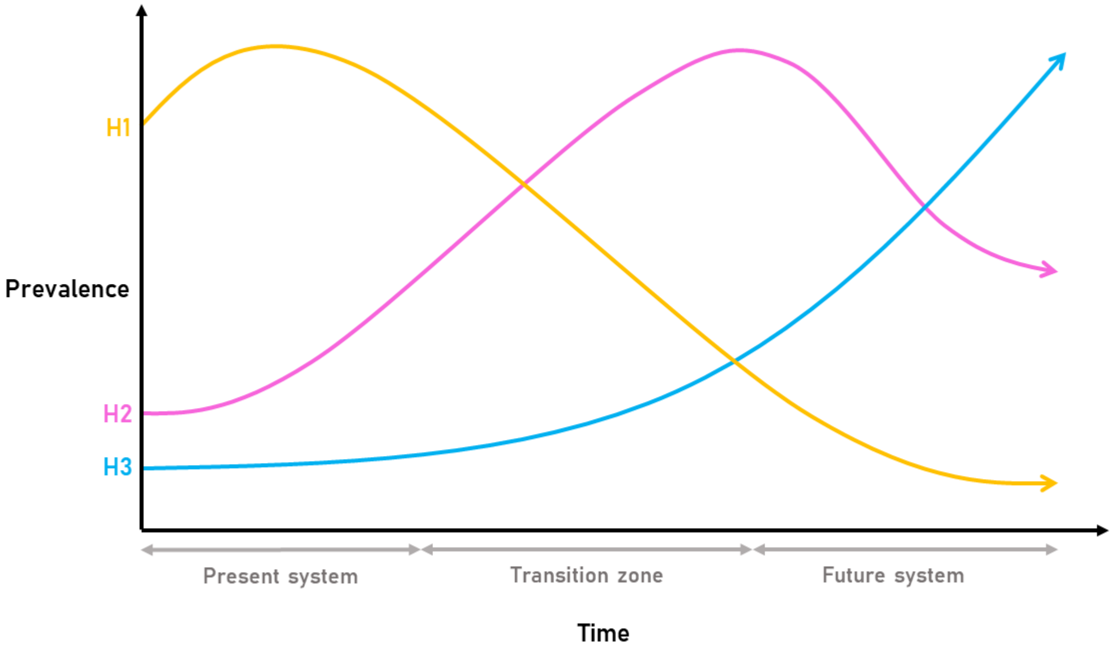

Figure 2.12: A graphical representation of the Three Horizons method. Adapted from Sharpe *et al.* [274].

ies. This involves appreciating the past, understanding the present, and forecasting, experiencing, envisioning, and creating alternative futures. Central to Dator's process, and to many other futures methods, is the value that constructing futures pathways brings. Indeed, Lum's Verge framework makes use of lived value in describing the levels of human experience using six domains: Define, Relate, Connect, Create, Consume, and Destroy, which can then be applied in forecasting and trend analysis [285]. Schultz, Crews, and Lum, in using the Verge framework to connect "impact cascades" from 'complicator' causal loops and 'attractor' scenarios [286] build upon Ogilvy's axes of uncertainty. Schultz, Crews, and Lum enhance the axes of uncertainty by bringing in elements of narratology[6] to dramatise the problem under investigation. They use Campbell's "Hero's Journey" framework [287], where adventures and crises unfold within a central story. They argue that through narratology, there is a space for turbulence to be incorporated within **H2**. Additionally, it also allows participants to embed characters into the futures system according to

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[6] Narratology examines how we use narratives to make sense of the world around us, and how they construct our realities.

Jungian archetypes such as the Outlaw, the Caregiver, the Sage, and many more [288].

Narratives make sense of experiences, and experiences are framed by narratives [289]. The use of narrative schemes in storytelling FL practices has enabled and encouraged different perspectives and worldviews. A wide array of SF meanings—Science Fiction, or Speculative Fabulation, for example—have been co-opted into FL, building on Heidegger's idea of 'worlding'[7] [292]. Liveley, Slocombe, and Spiers reflect on how narratives are instrumental in the construction of identities, and argue for the inclusion of storytelling practices in FL [187]. They argue that to operate with the principle of minimal departure[8], speculation within situated contexts can allow for the development of new contexts. By allowing FL practitioners to create an "augmentation of the self", they are then able to "embody and experience hybrid subjectivities" in generating futures. Marshall, Wilkins, and Bennett note that storythinking is a "practical model" that can aid transdisciplinary groups to playfully apply SFF (Science Fiction and Fantasy) creative writing to technological fields [294]. Drawing from Yanai and Lercher's concept of "day science" and "night science"[9] [295], they exhibit the value in creative FL and storytelling technological futures. They outline key themes for this practice: inhabiting future environments, empathising with the experiences of the future, envisioning plausible routes, and engaging by communicating through imaginative storytelling. Their case study with the Australian Defense Forces examined how their scientific challenges can generate social issues, and demonstrated how incorporating SFF futures thinking allows for

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[7] Heidegger's notion of 'worlding' is concerned with the interactions between actors and knowledge. In *Staying with the Trouble*, Haraway frames the practice of multi-SF worlding as an intimate disruption of familiar and "habitual ways of knowing" using narrative elements [290, 291].

[8] The principle of minimal departure is the extrapolation of what we know and are familiar with in the present in order to construct a future imaginary [293].

[9] "Day science" refers to practitioners adhering to rigid scientific disciplinarity, whereas "night science" refers to the exploratory and playful imaginables that arise from being unbound from the confines of day science. Day science would permit a laboratory chemist to only gather data to test hypotheses, whereas night science would allow them to imagine; much like Kekulé, whose chemical structure of benzene came to him in a dream where he visioned a snake devouring its tail [295, 296].

the deconstruction and reconfiguration of "shared realities" in collaborative narratives [294].

In order for this project to include considerations of how the future of the nuclear sector in the UK might unfold, it is crucial to draw upon current perspectives within the field of futures thinking and practice that consider the entanglements and complexities that lie within any future-oriented speculation. Contemporary perspectives within the field of futures studies emphasise the importance of speculative, creative-critical approaches[10] to futures work. These allow for considerations of social entanglements and multi-system complexities to be embedded into futures through different frames of reference. Indeed, the challenge—and strength—of creative futures work lies in the plurality of visions. Futures are multiplicitous because they are always imagined and created from a time and a place, and are often visualised amongst futures scholars using a 'futures cone', where the likelihood of particular futures occurring can be mapped. On futures cones, and particularly the multiplicity of futures, Gall, Valet, and Yannou discuss how "Futures studies is not about finding the one likely future, but the multiple possible futures" due to the "unpredictability and unconventionality of futures" [298]. The inherent multiplicity of futures necessitates mixed genre methods in order to provide a snapshot of the complexity of worlds, lives, time, emotions, and futures. An example of this is in Van Beek and Versteeg's study, which brought into conversation climate change modellers and climate fiction storytellers, finding both commonalities and differences between the quantitative futures methods used by the former group and the latter's use of experiential engagement [299]. By embracing complexity, this allows for divergence from simplification and homogenisation when undertaking futures work, which empowers researchers to include a diversity of voices and enables futurists to capture both the expected and the unexpected [300].

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[10] Creative-critical approaches inject an element of creativity into qualitative research in order to increase understanding of the world and make meaning of relationships [297].

Liveley, Slocombe, and Spiers argue that narrative approaches to futures literacy are important when forming critical and imaginative futures [187]. In experiencing the past and present, we become our own points of reference when thinking about future worlds, drawing upon and bringing in our lives and observations as foundations to construct imagined futures. Through this, our positional understandings facilitate world-building and making meaning of speculative futures, and we are able to engage with how social interconnections might evolve in shared material spaces. There is an inherent epistemic uncertainty in thinking about futures; one can never fully predict the future with complete accuracy. Further to this, there is also difficulty in imagining the future, as we tend to exist mentally in the past and present; extrapolating anything entirely 'new' from our position in the present is mentally challenging for humans as the present consumes our imagination. The question of uncertainty and moving past the present in futures is addressed through the tools of immersion and estrangement. Immersion focusses on involved engagement that is aided through plausibility, and estrangement is a mode to confront audiences with the alterity of futures—breaking the imaginative prison of the present. Spiers *et al.* demonstrate the use of immersion and estrangement with artefacts in the virtual reality environment "Museum of the Future" [301]. Here, the authors argue that "world-building is an exercise in deviation", that is, forming a future world is established on divergence from the present environment. Working within imaginations, the use of immersion and estrangement techniques in futures practices presents powerful opportunities for broadening futures thinking. The principal argument of Spiers *et al.* in "Museum of the Future" is that in exploring futures, audiences need to be immersed to an extent such that they do not disengage, and also unsettle their preconceptions of the present through estrangement technique to bypass their existing assumptions about the future.

Immersion and estrangement can be seen when futures media create environments to facilitate a story. For example, Porritt's *The World We Made* as mentioned in Chapter 1 [173] constructs a world through vignettes, chronological storytelling, and discursive modes. In Porritt's work, the immersion comes through the reader's familiarity with the workings of society and the climate, while the reader is estranged through the introduction of new technologies and the retrospectiveness of a future that mostly does not yet exist. On works that focus on climate futures, Silcox argues that by initially "unworlding" the world, this liberates avenues for ecocriticism – staying-with ecological catastrophe and collapse in the Anthropocene [290, 302] in order to confront our existing ideas of climate futures. In a similar vein to Porritt's work, the speculative online multimedia story *17776* [303] tells the story of space probes observing an immortal and infertile species of humanity as they play evolved games of American football over aeons, and explores humanity and consciousness. *17776* uses text, YouTube videos and animated gifs of Google Earth to progress the story temporally and spatially, immersing the audience through these familiar means. The estrangement in *17776* lies in the characters and the setting; the space probes are in outer space and communicating over large expanses of time, whilst on earth, a football game is taking place over a number of US states.

In futures media, artefacts can often facilitate the capacity of futures literacy and shape pathways to future worlds. As Spiers *et al.* note, "what stories we produce from artefacts, how and why we stitch them together, and how our ideas about the future can have an impact upon how futures unfold" [301] are important questions when considering the fact that futures are a type of discourse—they do not yet exist, only in the way we talk about them in the present. The effectiveness of speculative artefacts is such that governments that create policies are increasingly relying on this implementation as a mode of engaging the public in shaping their futures. For example, the Defence Science and Technology Laboratory (Dstl) – which is part of the UK government's Ministry of Defence – collaborated with futures practitioners in 2020 over a period of eight months to create the "Museum of the Future", which has influenced civil servants to think more strategically and creatively about the future of warfare and defence as well as the future more generally [301]. Furthermore, Welsh government bodies have engaged with futures practitioners to evaluate the intersections between communities and climate change in the artefactual construction of narratives through postcards, over a period of seven months between 2021 and 2022 [304]. Futures researchers have also created exhibitions that involve governments as primary facilitators of progress, such as “Carbon Ruins”, developed in 2019 [305]. Set in 2053 and commissioned by the Swedish government, “Carbon Ruins” presents artefacts from the “fossil era” – the time before Sweden had reached its net zero carbon goals by 2045 – which Raven and Stripple argue allows for the complexities of futures to be addressed [306]. These examples thus show that speculative artefacts do not belong solely in the realm of fictional endeavours; they constitute a mode that has been utilised seriously by governing bodies in their capacity to inform policies.

In *Futures Beyond Dystopia*, Slaughter critiques SF and FL methods and describes limitations in futures work [307]. He claims that “futures writing ... tends to be created on the basis of unexamined cultural assumptions”, such as the predomination of the Western-centric worldview and the dominating influence of technology on social innovations, which are both common in futures work. Instead, he suggests embracing alternative assumptions, such as moving away from the idea that the Western worldview provides a complete view of the world, and considering that new technological innovations are not the primary matter in social change.

Technologically-oriented futures work has benefitted greatly from informing futures through narratives, such as using role-play and wargaming to evaluate Artificial Intelligence (AI) futures and conflict resolution [308], and examining the role of machine intelligence in realising transhumanism through SFF and micro-fictions [309], amongst many other examples [310–317]. An important aspect of the conversation around technological futures revolves around automation and AI [318].

Without question, the realm of AI has grown considerably, with the emergence of AI-generated art [319–321] and text-based chatbots such as ChatGPT [322–324] inducing social and cultural dilemmas [325, 326]. For climate change in particular, automation and AI concepts have been evolved to analyse dynamic climate data and manage forecasting uncertainties [327–330]. To explore the extent of the involvement of automation and AI, Frase examines the aftermath of capitalism using descriptive scenarios in *Four Futures* [331]. Through claiming that automation and climate change constitute a dual crisis in a postwork future, Frase creates four futures, displayed in Table 2.2 according to the dimensions they occupy: abundance and scarcity of resources, and equality and hierarchy within society.

	Abundance	Scarcity
Equality	Communism	Socialism
Hierarchy	Rentism	Exterminism

Table 2.2: Frase's four futures: Communism, Rentism, Socialism, and Exterminism, illustrated according to the dimensions they encompass [331].

For each of the futures in Table 2.2, Frase discusses the specifics and societal ramifications [331]. Firstly, communism is concerned with the freedom that is reclaimed from working less due to living in an automated world; a utopian vision where "resource and ecological limitations [are] transcended through better technology". Rentism, where intellectual property is withheld by the economic elite and stymied due to class structures, centres around "power and wealth [maintained] in an environment of total automation". Socialism focusses on living together in a damaged world as part of an egalitarian society. Here, environmental, as well as human social limits dictate how we must live, in the process rebuilding environmental relationships and reconstructing lives through community infrastructure. There would be stronger attachments made with technological innovations in a socialist future, given that resources would be scarce [332]. Finally, exterminism involves the genocide of the "inconvenient" masses through algorithmic targeting, dehumanisation, and widespread militarisation, controlled by a small elite. Interestingly, there are elements of transition between the four futures; for example, exterminism can transition into communism for the elite after the elimination of the working masses. Much like other FL concepts, there is fluidity between possible scenarios through the transformations that emerge alongside new technologies, highlighting how we change and are changed by futures. On the road to these four futures from the end of capitalism, Frase stresses that “the path that leads to utopia is not necessarily itself utopian”, and that better futures for one particular group are not necessarily better futures for other groups. By being mindful of the brutality inflicted along futures journeys, we can endeavour to explore how technological innovations can effect change in the communities inhabiting a diverse set of worlds.

Time is an important dimension of futures thinking. The passage of time, and the concept itself, allows for the delivery of the futures that we potentialise. We think about time differently, depending on our lived experiences, cultural understandings, and forecasting capabilities [333–335]. Contemplating time is crucial to both short- and long-termist thinking, with the latter posing more challenges due to the difficulty in transcending thinking beyond human lifespans. Although the near future can be envisaged and tentatively planned for, the same cannot necessarily be directly applied to the extreme end of far-sighted futures, where deep time lies. Encompassing not only the Earth’s early geological history, but also its landscapes in far-flung futures, deep time is a concept that encourages thinking beyond human capacity through observing changes in the Earth’s geological formations [336], and examines lengthy timescales, from thousands to billions of years. Deep time is especially pertinent to nuclear power as some isotopes that are generated during nuclear processes possess long half lives; for example, plutonium-239 is an isotope that is generated from the neutron capture of uranium-238 in a reactor, and has a half-life of 24,100 years [337]. In *Deep Time Reckoning* [338], Ialenti explores this idea by discussing a Finnish nuclear disposal company’s safety assessment report concerning a then-prospective waste repository, Onkalo, on Finland’s Olkiluoto island, where two fission reactors are located. Through contending with a "deflation of expertise", Ialenti's ethnographic and anthropological research reveals new comprehensions pertaining to futures practices: making analogies across space and time to ontologically compare past and future worlds; using causational patterns to model far futures; adopting multi-angle and multi-scale perspectives to view both the bigger picture and minutiae of a futures problem; and "predecessor preservation" in order for expert knowledge to be survived. Perhaps, by implementing these deep time reckonings for not only the Onkalo spent fuel repository, but for nuclear power generally, we can potentially begin to better imagine futures adhering to the extensive timescales of nuclear power.

Together, these contemporary perspectives in the field of futures studies that I have outlined above have influenced my research, enabling me to build upon them to create my speculative world. In the process of conducting futures research, I combined much of the content in the empirical data that I obtained from my participant research with the leap of the imagination through the worlding technique of speculative storytelling in order to create the artefacts in Chapter 6. Using the tools of immersion and estrangement, the creation of characters and speculative artefacts, e.g. government reports, newspapers, and social media posts, and considering temporality in futures by creating speculative snapshots over a period of six years, I have envisioned a possible nuclear future that involves our knowledge of material behaviours on an atomic scale, and current and past societal impacts of and on nuclear power.

In this chapter, I discussed the methodologies that I used in this thesis, which enables me to explore original research avenues, as can be seen in Figure 2.13. In the next chapter, I present my qualitative research into nuclear power and ATFs, providing more context for the materials science research presented in the following chapters and for the creative-critical future in Chapter 6.

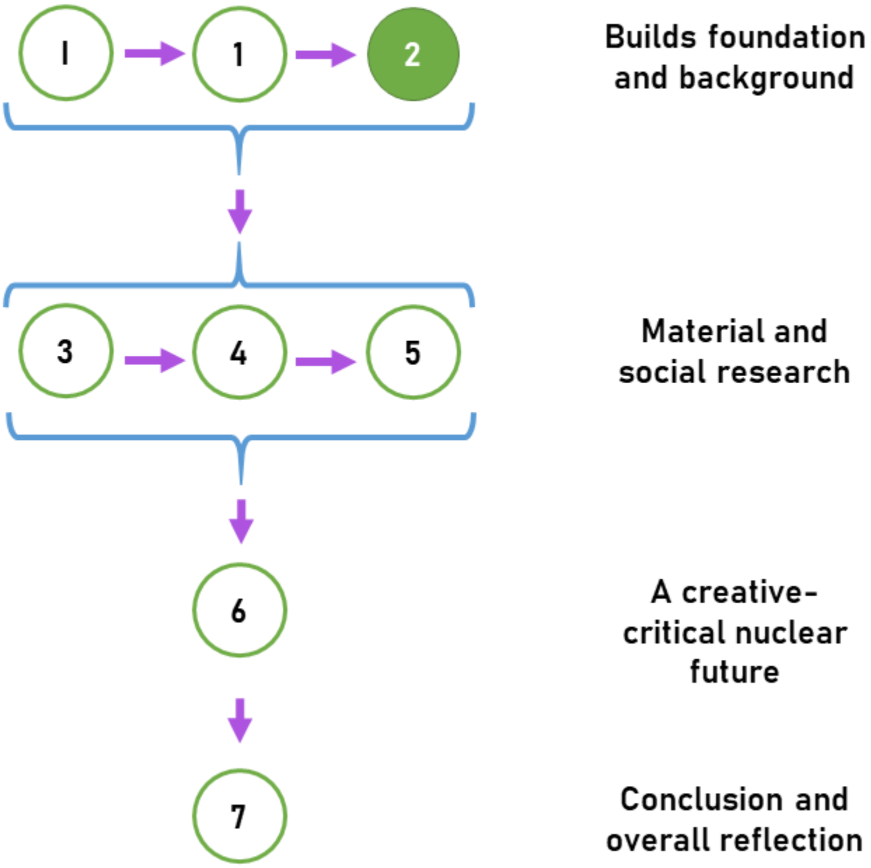

Figure 2.13: A map of the thesis structure. The chapter that we are in now (‘2’) has provided the fundamental theories and methodologies that I have used in this thesis.

Chapter 3

Narratives of nuclear power

In the previous chapter, I discussed the methodologies and underlying theories of my research. In this chapter, I explore attitudes and sentiments around nuclear power through qualitative research and participant interviews to obtain a variety of perspectives around nuclear energy. In doing so, I provide the material needed in order to be able to answer my research question: "*Can a creative-critical future be produced using a Material Social Futures perspective, and what will that look like?*", as the data collected in this chapter provides existing narratives around nuclear power.

3.1 Introduction

With nuclear power being an area of immense interest in today's ever-changing energy landscape, its complex social, historical, and political connections must be explored in detail by uniting the physical sciences and humanities. In order to provide a holistic overview of the socio-political and historical significance of nuclear power in this way, I have captured and collated the collective and individual experiences of nuclear power in the UK in this chapter. From the media reports and interviews, the speculative insights gained through the current narratives are important as they implicitly bring nuclear technology into the conversation, and hence this is important for developing and researching technologies, like I do in Chapters 4 and 5. I carried out the archival research, which informed the content of the semi-structured interviews, using material from the Lancashire County Council archives in Preston, as well as data from online archives.

This chapter will aid in understanding the sector, the people, and the values relating to nuclear power. In many ways, it sets up various topics which I will address in later chapters: Chapter 4 and 5, which focus on the thermophysical properties of UN and the behaviour of fission products within UN, presents new knowledge resulting from concrete physical concerns surrounding nuclear fuels, and the potential for future nuclear technologies such as ATFs to address some of these social concerns arising from the qualitative research presented in this chapter. The resulting knowledge from stakeholder interviews then form the foundation of chapter 6, which provides a speculative narrative perspective of the findings of this chapter, and allowed me to consciously unearth the entanglements within nuclear futures and make them visible in narrative form.

In this chapter, various references to nuclear accidents will be made, such as:

- Three Mile Island — Pennsylvania (1979): LOCA involving a partial core meltdown.
- Chernobyl — Ukrainian Soviet Socialist Republic (SSR), now Ukraine (1986): poor reactor design and mismanagement led to an explosion and fire.
- Fukushima Daiichi — Japan (2011): a LOCA that occurred when a tsunami struck the reactor.

For these accidents, common themes appeared in each of these time periods which will also present themselves in this chapter, such as the emergence of activist and opposition groups, media reactions and anxieties, and concerns over jobs, public health, and considerations around nuclear waste. This chapter will reveal that these themes materialise consistently throughout time and highlight the commonalities that nuclear power evoke.

In this chapter, my intention in unpacking and pulling out the nuances of the different types of discourse in the interviews is not to judge whether what the interviewees are saying makes sense or whether they are right or wrong, but to unpick the various threads of discourse that exist and the multiple perspectives that exist and take them seriously in this work. This is important because some of these voices are not taken into consideration when planning for nuclear futures, and this thus leads to tension and misunderstandings in the sector. In including a variety of perspectives in this thesis, I hope to exemplify that many different perspectives are necessary when considering and creating nuclear futures for all.

3.2 Documentations of nuclear power

Combining archival research with interviews that explored current attitudes and perspectives enabled me to make connections between attitudes and perspectives in the past and the present, and allows the various themes and shifts in discourse to be uncovered along the timescale of nuclear history. Weart [15] describes public acceptance and marvel as a general response to early nuclear experiments in the form of ‘transmutation’ in the scientific sense; such a novelty and its promises of “a pint bottle of uranium containing enough energy to drive an ocean liner from London to Sydney and back” was met with excitement. Over the decades, and due to nuclear disasters, attitudes have evolved from these early unwary reactions to nuclear power. Edwards [339] details various studies around psychological experiences of nuclear power, focussing on the effects that the Fukushima Daiichi and Chernobyl accidents had on the public. The discussion highlights the influence of different factors on attitudes towards nuclear power, such as the level of perceived danger in power plants, and a lack of trust towards authority figures. The importance and relevance of qualitative research in the nuclear sphere is also highlighted by Edwards, who states that “findings from quantitative research have the capacity to inform qualitative research questions, and vice versa". Prevailing attitudes towards nuclear power and its associated impacts can inform public discourse and affect conversations and relationships between nuclear organisations and communities. For example, the nuclear industry often posits nuclear power as a "low risk and affordable" source of energy [340], but there exists strong resistance from concerned members of the community, to the extent of forming activist groups such as Together Against Sizewell C (TASC) [341].

3.2.1 Fears and concerns

The rapid advancement of science and technology in the early to mid-twentieth century bore fresh industrial innovations and enabled the advent of purposeful nuclear power, with the world's first nuclear reactor—Chicago Pile 1, built in 1942 [342]—to pave the way for the large-scale use of fission in nuclear power stations, the first one being the Windscale nuclear reactor in north-west England. The development of nuclear power and its prospects reinvigorated discussions around the future of energy generation, however, a rise in anti-nuclear sentiments was also seen after the usage of nuclear warfare in the Hiroshima and Nagasaki bombings in 1945, with protests such as the Aldermaston March in 1958 [343] indicating a growing desire to suspend nuclear proliferation. The zeitgeist of this time period was mainly characterised by a fervent dedication of many in asserting their campaign for a more beneficial future in which to live and thrive.

Heysham 1 is a fission power plant in the village of Heysham, situated in Lancashire, not far from the university where I conducted the present research. After planning was completed in the 1960s, construction began in 1970 and operation began in 1983 [344]. The power company overseeing the development application for Heysham 1 was the Central Electricity Generating Board (CEGB). As the construction plans were reported in the media, public opinion on Heysham 1 became divided, in ways that demonstrate the historical importance of tourism for the region. A local leisure resort owner commented that “a nuclear power station will certainly be better looking than the Trimpell factory[1] and much more of a tourist attraction”, whilst diminishing the seriousness of the Windscale accident, noting “the elaborate safety precautions taken at all such establishments and how much progress has been made since the Windscale mishap” [346, 347]. Yet, Alderman Norman Edmonson, who was the chairman of Morecambe’s planning and development committee “thought such power stations were ‘rather large and overbearing’ ”, and insisted the committee would “fight the project” based on aesthetic concerns, rather than those of safety [348].

Newspapers in the mid-twentieth century amplified various voices that adopted either a supportive or an opposing stance, and demonstrate a focus on employment opportunities in the face of the region’s waning trade in tourism in an era of more affordable plane travel, on the one hand, and emerging energy technologies, on the other; one article bore the headline “Atom plant will provide 500 jobs” [349], whereas in 1968 the West Lancashire Evening Gazette described a demand by Mr Michael McGuire—MP for Ince and branch secretary for the National Union of Mineworkers [350]—to “refuse permission for the proposed nuclear power station at Heysham”, arguing that “electricity from coalfield stations is cheaper despite the considerably greater capital cost of the nuclear stations” [351]. Championing the continued use of coal mining, McGuire elaborated on his thoughts in a 1968 Commons debate on siting nuclear power stations, where he stated that his “right hon. Friend should hesitate very long before deciding to build in this way, because it is a new and untried technology, and the results, if anything goes wrong, could be disastrous” [352]. Here, he promulgated sentiments of trepidation whilst protecting his financial interests relating to coal stations. Such feelings of unease towards an unfamiliar industry in a county attributing its industrial success to cheap, local coal [353] was therefore to be expected, and with the technology’s tainted reputation from the atomic bombings

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[1] The Trimpell Oil Refinery was a chemical works site that was built during the Second World War [345].

in 1945, it was not unnatural for concerns to develop and permeate. However, many of the concerns seen in these archive materials tended to concentrate on factors unrelated to safety, such as employment and potential effects on tourism, and instead furthered negative narratives to support their arguments.

As plans for nuclear power plant developments are unveiled, there is often clear opposition from various stakeholders. Sizewell C is a nuclear fission power plant proposed by EDF Energy and China General Nuclear, set to be located near the existing Sizewell A and B reactors in Suffolk. Public consultations took place for these proposals from 2012 to 2019, with documents published online and in print containing information and questionnaires regarding the plans [354]. These consultation documents mainly focussed and sought feedback on accommodation, transport, tourism, and ecology, whilst illustrating the advantages of Sizewell C. Community forums took place concurrently with these public consultations; representatives from the surrounding area gathered to discuss the proposals with a panel composed of officials from EDF Energy, and listened to presentations on the latest developments. The minuted community forums were an opportunity for direct challenges to be made by representatives, and for ongoing changes to be monitored and debated. Broad representation was seen at these forums—MPs, councils, ecological organisations, and anti-nuclear activist groups such as TASC were all in regular attendance [355]. In most of the forums, the plant proposals were scrutinised, and the concerns were able to be expressed towards the project: Jon Swallow, of the Sizewell Parishes Liaison Group, said that “looking at details of [the campus proposal] was like ‘rearranging the deckchairs on the Titanic’ ”, and that “the whole scheme needed fundamentally rethinking” [356]. This striking comparison to the most famous sinking liner highlights how residents believe EDF Energy to be ignoring major issues, and that no amount of “rearranging the deckchairs”—shuffling the problems around—would sufficiently solve these detrimental issues. In the same forum, Thérèse Coffey, MP for Suffolk Coastal, “stated that she was shocked by the presentation and that it seemed that EDF Energy had not listened at all to the concerns of the community" [356]. Coffey added that "EDF Energy needed to 'get real' about the needs of the people who were going to live with the development for over 10 years", making clear the power imbalance felt by many in the local communities: EDF Energy an unstoppable force, and activist groups a movable object in this struggle of serious and permanent change, and signalling a somewhat deteriorating relationship between companies and community groups.

Feedback from later-stage consultations reported that "concerns had been raised in relation to noise pollution, artificial light, fluctuating water levels and coastal erosion and the impacts on wildlife" [354]. The representative for TASC, Joan Girling, chose to comment on the "size of potential buildings" and the "exact acreage of the site" [357]. It should be noted that the complaints related to the size of the Sizewell C plants echoes those raised for Heysham in the 1960s [348], demonstrating how the same concerns can surface at different points in time from dissimilar groups of people.

Common concerns appearing repeatedly over time were also observed in other ways. In 1969, the Morecambe Visitor featured views from the County Publicity Office over delays at Heysham: "Already Ministerial dilly-dallying has put the programme back two years. It would not be so bad if some clear indication was given as to when a decision is likely. As it is we are completely in the dark and it seems to be getting darker all the time!". Additionally, the County Publicity Office opined that the general public are "forever being told to get off our backsides and work industriously to get the country back on its feet. We feel the same message is applicable to the Minister of Power – unless, of course, his Ministry is power-less" [358]. Contextually, the political landscape of this time was defined by many periods of austerity [359], and the vivid symbolism of 'darkness' indicates the fear and mistrust that Edwards records [339], whilst the sentiments held towards the Ministry are particularly condemning. Feelings towards delays at present echo feelings towards delays in the past, as Hinkley Point C was branded as having a “financial quagmire” [360], whilst “vital information” in its documents was felt to have been kept “away from the public” by the Department of Energy and Climate Change [361].

As I have already noted, employment was another common concern regarding nuclear power. Wylfa Newydd was a proposed nuclear power plant to be situated in Anglesey, Wales, with its plans currently retired due to funding issues. Public consultations were held for Wylfa Newydd, and one particular item of feedback in 2016 detailed the “concern regarding the potential for displacement in the local labour market,” adding that demand for local labour would be increased “such that it could distort the local building market, resulting in a reduction of available builders for all other projects” [362]. Similarly, the Lancashire Guardian writes in 1967: “local building contractors are not happy about the future because they fear skilled workmen will be lured to the nuclear site by high wages” [363]. In the same year, the Lancashire Evening Post published the views of a farmer, who “predicted that the nuclear power plant would ‘kill off’ farms for miles around”, explaining that if their farm is sold, they would be “turned out” and “looking for a job” [364], implying perceptions of dispensability. The theme of ‘darkness’ resurfaces here, as the farmer states “we have been told nothing yet. All we know is that the farm is right in the middle of the proposed power station site”. It is noticed from this comment that the power companies did not make efforts to engage with the members of the public that were most impacted, instead leaving plans wrapped in secrecy.

After the Chernobyl accident in 1986, there was a noticeable shift in the tone and language used by energy companies in their attempts to engage with the public. Nuclear Electric, which emerged from the disbanding of the CEGB in 1990 [365], attempted to be more transparent, evident in a letter sent to members of the Heysham Power Station Local Community Liaison Council (LCLC) regarding a then-upcoming study on the link between radiation exposure of workers and childhood cancer and leukaemia. Nuclear Electric begins the letter with a brief: "I am writing to you about an issue that may feature in the media from today", and proceeds to "welcome the publication of the study" in the British Medical Journal. However, in bolded text, they state: "the study does not support the hypothesis, proposed by Professor Martin Gardner in 1990, that irradiation of a father before conception of his children is a cause of childhood leukaemia; nor does it cause other forms of childhood cancer," and that "the results do lend weight to the hypothesis by Professor Leo Kinlen that raised incidence of childhood leukaemia is due to infection from high levels of population mixing" [366]. The timing of this letter is significant in that Nuclear Electric were clearly seeking to pre-empt media coverage of the article in order to 'get ahead' of the possible narrative framings that the media may construct; there is an urgency to 'dispel' potential disinformation and to take control of the narrative locally, with the choice of bolded typeface furthering this urgency. The calculated manner in which Nuclear Electric addresses the LCLC suggests awareness of fears and anxieties surrounding nuclear power, and indicates that they had become more clued up about how important information and narrative framing of such information had become, consequently seeking to control what residents understand as the 'true story' to their benefit.

Towards the end of the twentieth century, Nuclear Electric showed continued attempts at controlling the local nuclear narrative through communicative transparency in their communications, with a semi-fortnightly newsletter, Heysham News, released to residents in and around Heysham. This newsletter gave thorough updates on the conditions of the reactors at Heysham, and shared their generation data: "Since the last newsletter, Heysham 1 has supplied 286 million units of electricity to the National Grid Company (NGC) ... During the period Unit 1 has generated 199 million units and is currently operating at 593 MW(e)" [367]. Furthermore, the information surrounding the operations at Heysham was intended to contain a high degree of clarity in writing and publishing Heysham News; minor events that had occurred were reported on, such as “higher than expected readings [of radiation][being recorded] from a portable vacuum cleaner”, which was “immediately placed in an appropriate control zone” [367]. The prompt actions regarding the portable vacuum cleaner conveyed here portray a sense of reassurance and also a responsibility to reassure. In each issue of Heysham News, a section titled “Visitors Centre” outlined the statistics of public traffic to the power plant. As the company that headed a facility whom many deemed to be a risk, Nuclear Electric was poised to allay post-Chernobyl fears as much as possible, and these newsletters served as a courier signifying progress and operational competence in times where questions and uncertainty over nuclear power were prevalent.

3.3 Research interviews

The interview questions were formed around the motifs unearthed from the archival research, with an aide-mémoire—in Appendix C—created to logically order the questions. The questions were designed to systematically probe the interviewees, as well as for comparability purposes in the analysis stage. By conversing with the interviewees in individual interviews, this allowed for more time and space to fully explore personal thoughts and ideas. In such circumstances, it is important to further explore my positionality as a researcher with respect to the interviewees, and how it may affect their attitudes in the interviews.

Throughout the interviews, my role as a researcher heavily defined my positionality, projecting a clear distinction between myself and the interviewee. The assumptions that the participants make about myself and my research would affect the knowledge they impart and how they convey that knowledge. I am at once both the observer and the observed; the participants perceive me with their own understanding and intuition and so respond to my queries with their own deductions in a certain manner. In particular, my association with Lancaster University provides credibility to the significance of this study alongside justifying the interview and the participants' involvement. However, my association with an academic institution implicitly prevented me from possessing the positionality of an external individual, leading to less personal or more persuasive changes in the responses of the participants. The academic hierarchy also situated me as a postgraduate researcher relative to other academics—this arose in particular during my interview with Wade Allison, who is an Emeritus Professor of Physics at the University of Oxford. This categorisation constructed a teacher-learner dynamic, rendering the interview to be conducted with an educational undercurrent.

The power dynamics that emerged from my positionality directed the way the participants framed our interactions. Prior to my interview with Janet Fendley, we exchanged a series of emails in which I introduced the study and the interviews, which were held online due to the COVID-19 pandemic. Janet urged me to visit her home and the surrounding area, and to conduct the interview in her garden. The suggestion of sending photographs of the landscape that she wanted to communicate to me was criticised as not being able to "give [me] the feeling of the place", and that my understanding would be "limited" by a virtual interview, ultimately expressing disappointment. Here, Janet imbues me with possessing a set of characteristics that reflect her understanding of the power I hold as a researcher, and activated an emotional response that drew upon preconceptions of the outcomes of the interview in order to effectively persuade and add evidence to her responses. My physical experience of Janet's life and her surroundings was thus crucial to her explanation of her personal nuclear narrative.

Fluctuations in my positionality materialised during some instances in the interviews, particularly when emotive topics were discussed. Janet, towards the end of our interview, became tearful when discussing her grandchildren in relation to the future of nuclear power. The mournful response that surfaced was powerful, and I found myself overcome with emotion, to the point that I attempted to hold back tears whilst listening to her. This entire interaction surprised me, as I had not anticipated for the interviews to be, to an extent, laden with emotion. As Tanner notes, "unexpected encounters … [make the researcher] more of an active participant than an observer in [an interviewee's] life stories" [368]. This particular encounter actualised a vulnerable facet of my character, which consequently reframed my positionality with respect to Janet and her understanding of the power dynamic in our interview.

Alongside Janet, the other advocates of and against nuclear power also gave personal reasons when explaining their relationship with nuclear energy. By referencing their lived experiences in their interviews, the affective associations that they established with me enabled them to convince me of their viewpoints—this persuasion in addition to these participants so readily agreeing to be interviewed was in part due to them perceiving me as having involvement in the nuclear power industry and ultimately holding power. This power was lessened slightly when, at the beginning of each interview, I asserted my recognition of the interviewee as an individual with experience and insight in order to explain the motivation of this study. The dynamic would shift again as the agendas of these participants were present during the interviews, particularly as many of them belonged to lobby groups and approached the interview as a representative of a particular organisation, conversing with an outsider.

Limerick, Burgess-Limerick, and Grace reimagine the roles that emerge and change during interviews, and discuss the personalisation of interviews in the context of the interviews as "gifts of time, of text, and of understanding" [369]. In this study, some gifts were felt to be easier to receive than others, owing to many different factors and perceptions. One notable factor was age. This was quite significant as part of the interviewer-interviewee relationship such that Allison sent a follow-up email to my supervisor identifying me as a "young [person]". All of the participants

I interviewed were older than I was, creating an unspoken authority for them and a more considerable barrier to the personalisation of the interview. A greater degree of trustworthiness could be established by conducting repeated interviews in order to build rapport with the participants and validate narratives and meanings. Our relationships and interactions could also be reinterpreted with each successive interview, further shifting the power dynamics present and allowing for the participants to reassess me as a researcher.

The interviews that I conducted with the sector employees were markedly different from those with the activists. Instead of sharing their personal experiences, some of them adopted personas that were dictated by their companies, and provided formal, constrained answers that reflected their understanding of their positionality in their workplace and in the interview. There was an expectation that any of their responses in the interview could be used for this study and hence published, hence their recognition of this power dynamic led them to be cautious in their manner of communication. One spokesperson chose to keep their camera off, which served as an additional barrier to non-verbal communication and allowed for a distance to be maintained to further their own understanding of my positionality. I chose to use expressive movements with the interviewees to signal my interest in our dialogues and demonstrate to them their value and importance whilst encouraging them to continue their response to gain as much insight as possible. Non-verbal behaviour is especially salient in interviews as it can usually be translated verbally, to either extend or disguise the underlying meanings in the conversation [370]. The spokesperson's removal of kinesic communication therefore made the interview difficult to sustain, as my body language, facial expressions and gesticulations were unreciprocated and changed the social context of the interview. This interview was considerably shorter than the others as it was deliberately depersonalised. Nevertheless, valuable narratives were gained from what was mentioned and from what was omitted.

For many participants, their professional relationships with nuclear power were an equally important part of their identity; some more so than others. In particular, the representative for Nuleaf stated that their relationship was a strictly professional one, mentioning their “agnosticism” toward nuclear power. There were uninhibited and jovial undertones in the interview with this participant as they may have noticed a similar embodiment of agnosticism in myself and my research, thereby causing the elements of power in the interview to contain a degree of moderate neutrality. The interpersonal relations that emerged in the interview were largely due to the participant’s motive being that of promoting Nuleaf’s activities and themes. Here, there is a greater balance of power; the participant is a knowledgeable agent who selects expertise to share with me and I correspondingly have a significant responsibility in communicating their ideas. Despite this balance, complex power shifts were maintained throughout this interview via the interview medium, the information that both parties involved chose to divulge, whether the narratives were personalised, much like the rest of the interviews.

3.4 Thematic groupings

Gathering the summary of insights for each interview enabled themes to prominently appear across the interviews. This section details the thematic groupings that arose from the discourse analysis of the interview responses, which uncovered the sentiments and subject threads present in the discussions. Linkages and commonalities were found between all participants within and between the themes that emerged as a result of discourse analysis. The interconnections between themes are illustrated in Figure 3.1.

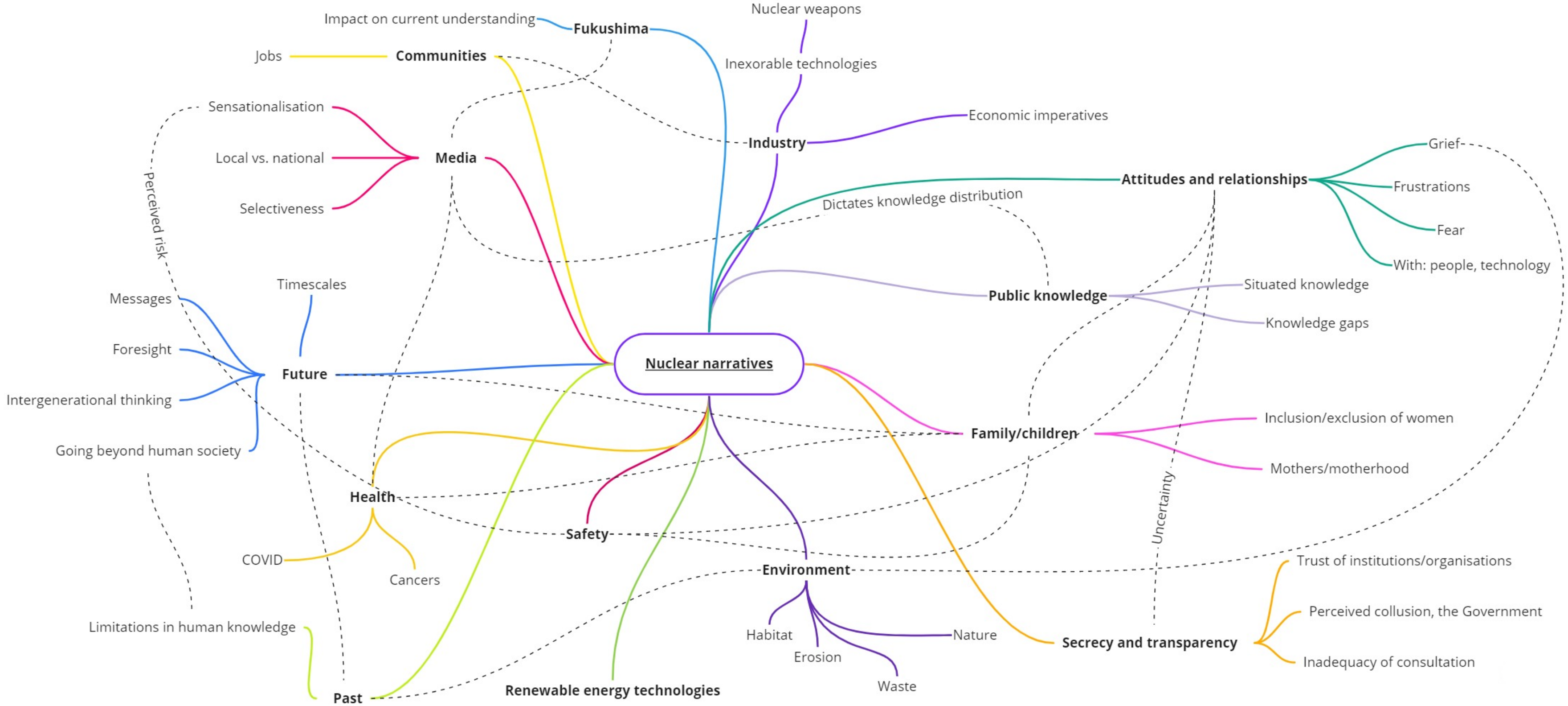

Figure 3.1: A visual representation of the connections between the major themes arising from the interviews. These central themes are depicted in bold, and along with the sub-themes that branch off, are connected to other major or minor themes with dashed lines.

When reading the quotations and excerpts from the interviews, it should be kept in mind that such fragments of the conversations are reflections of the thoughts and feelings of the participants at a particular time and place in the summer of 2021. At the time of writing these analyses are more than a year old, many changes have taken place both globally and in the UK; the war in Ukraine, rises in living costs, and the approval of funding for Sizewell C are but a few of the events and realities that have affected many members of the population, including the interview participants. As stated in Appendix B, participants who chose to protect their personal identities will be referred to as numbered participants.

3.5 Narrative themes

After identifying the themes emergent from the interviews, it was possible to gather the most pertinent ones into four major thematic clusters, visualised in Figure 3.2:

- **Environment**: including issues relating to – Environment, Renewables, Safety, Health
- **Fukushima Daiichi: a case study**: including issues relating to – Fukushima Daiichi, Industry, Communities
- **Attitudes and attachments**: including issues relating to – Attitudes and relationships, Public understanding, Secrecy and transparency, Family and children
- **Discourse and narratives**: including issues relating to – Media, Timescales, Past and Futures

Each thematic cluster represents the related issues that emerged across all of the interviews. With there being overlaps between many of the themes, I selected the main ideas present in each theme according to the points of discussion in the interviews; for example, in the Fukushima Daiichi thematic cluster, the case study contains elements relating to the accident, the industry response and the role that

Figure 3.2: A visualisation of the four thematic clusters.

it played in the accident aftermath, and the intersections with the communities around the reactor, directly quoting as well as drawing from the interviewees' views. Overall, the aim of these thematic clusters is to present a holistic picture of the themes, identifying the entanglements within and around nuclear power in the process. It should be noted that many interviewees were of a different generation than I; therefore their meanings around expressions such as “black and white" may be different to my understandings, and my analysis should be viewed through this lens of intergenerational communication.

3.5.1 Environment

The role of nuclear power in managing the effects of climate change has been a major point of discussion on the topic of sustainable climate action. More specifically, nuclear power has been regarded, and indeed marketed, as a technology for climate change mitigation [371]. However, perceptions have been observed to differ; previous research conducted by Poortinga, Pidgeon, and Lorenzoni found that of the members of the UK public surveyed over attitudes to nuclear power (n=1491), 39% believed that nuclear power causes climate change [372] and studies have also suggested that the limited impact of nuclear power in reducing greenhouse gas emissions necessitates the phasing-out of nuclear power plants [373]. Furthermore, Kopytko and Perkins address the problems in the climate change mitigation and adaptation of nuclear power, and find that adapting nuclear power plants to increasingly extreme climate change events is too costly and economically inefficient, and also compromises reactor safety [374, 375]. Given such discrepancies between intentions and actualities for nuclear power and climate change, there is much value in exploring the environmental aspects of nuclear power and connections to climate management.

A range of these perspectives were offered in the interviews. For example, Interviewee 5 believed that "the climate change issue is so extreme that you need every single solution you've got and nuclear is one of those", and Pete asserted that "we have to be realistic and energetic and decisive about the way in which we tackle the climate change crisis", adding that "if it's a crisis, we have to treat it like a crisis, we have to treat it like a pandemic and just throw everything at it". Some interviewees cited climate change as a driver for their attitudes and activism, such as Interviewee 6, who frequently raised the need for nuclear power to "tackle climate change", and conversely, Interviewee 8, who "[wanted] to see a cleaner renewable energy alternative" to manage the environmental issues around climate change.

In addition to climate change, there are other environmental considerations surrounding nuclear power—for example, in post-accident environmental contamination, in the siting of nuclear power plants on land near human populations, and in the underground burial of nuclear waste. The nuclear industry's reliance on land and the ways in which it transforms landscapes is a particular area of discord for some. For Janet, who lives near a conservationally-protected Area of Outstanding Natural Beauty (AONB), the issue of land use becomes personal due to her close connections with the environment. In my interview with Janet, she discussed the "huge environmental ... renaissance" in the 1960s as well as citing Rachel Carson's seminal book *Silent Spring* in her response describing her relationship with nuclear power [376]. Janet's reflections on the events of this period resonate with scholarship on the social movements of the time. As nations grappled with the ongoing Cold War, many societal identities became shifted, particularly in relation to environmentalism; Rome explains the impact that liberal movements, middle-class women, and the younger and progressively countercultural generation had on environmental activism in the United States; he notes the influence of the national politics surrounding pollution, as well as women's organisations, motherhood, and the act of "survival" on the personal intentions of environmentalism amongst young people [377]. The destruction of nature and the polluting of life only furthered the force of protective and sceptical movements, particularly where human health was concerned.

For the general public, Carson outlined the consequences of using pesticides in *Silent Spring*. Published in the early 1960s, the indubitably groundbreaking book made clear the downfalls of the use of toxic chemicals, and likened hazards from pesticides to the "threatening" nature of radiation. Government officials in the United Kingdom reacted to the outcry and criticism arising from *Silent Spring* and the concurrent sudden poisonings of animals in Kent in 1963 by establishing the book as a prominent reference [378], and by pursuing investigations into the cause of the poisonings, ultimately banning the use of the toxic compound fluoroacetamide for use as an insecticide [379, 380]. Clark observes in [380] that the actions of the Government contradict their previous stance, as they initially concluded that this was a solitary occurrence, with no wider impact on the environment. Used as a touchstone by Janet, the overlaps between the events of *Silent Spring* and nuclear power are in the notions of invisible harm and a lack of trust in the reassurance of authority figures over safety. After reading *Silent Spring* and witnessing the monumental impact of the environmentalist movements of the 1960s, Janet may have formulated her own responses to nuclear power associated with these events, paying particular attention to the contradictions of the Government and the impassioned voices of the environmentalist movements. Janet's use of the word "renaissance" provides a vivid image of the revitalisation of environmental justice, and cements her position in these movements and the strength of her activism.

Throughout the interviewees' discussions on the environment and nuclear power, there were clear themes of loss that emerged in the interviews, especially pertaining to habitats, nature, and communal agency. More broadly, all sources of energy generation require some level of environmental degradation; rare earth metals[2] [382, 383], fossil fuels, and uranium must be extracted from natural reservoirs, and building and maintaining sites for energy generation can require land interference. Particularly for Interviewee 5, the issue of depleting finite uranium resources was mentioned when discussing his concern for the sustainability of nuclear power, similar to that of fossil fuels. Loss in terms of land disturbance and destruction was a topic that generated a significant amount of discussion; upon discussing Sizewell C, Janet mentioned that "we're supposed to be protecting areas of outstanding natural beauty, we're supposed to be ... holding huge respect for Triple SI's[3] and yet somehow in East Suffolk that's overlooked". Continuing, she added: "We are so lucky with the birds and the other animals that live round here, the various flora and fauna that live here. It's so stunningly beautiful that I feel very privileged to live in such a beautiful place ... a very delicate sensitive habitat area". Elaborating on the subject of fragile ecosystems, Janet commented on the welfare of marine animals:

> Around the waters here apparently there's some protected, I don't know the

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[2] Rare earth metals are 17 elements in the periodic table that are commonly used in technology [381].

[3] A Sit of Special Scientific Interest (SSSI) is a region of land possessing special natural features [384].

> name of it but we have porpoises out here and we know that the noise will affect those marine mammals . . . , so the fish now, the EDF numbers for B and for Hinkley B, for Sizewell B and Hinkley B, the fish stocks that get destroyed, the numbers are huge. I mean it's millions of tons and the state of the fish in our oceans from overfishing is not healthy. So if you're destroying them from sucking in the water for the coolant, that's how it happens. I mean there are positives I suppose because the kittiwakes like to eat the fish, but . . . the marine environment as well as the woods and the marshes and the mitigation that EDF are proposing has got huge holes in it.

Janet's perception—that the solutions suggested by EDF were insubstantial—highlights inconsistencies in the thoroughness of their planning and decision making; she elaborated:

> The beach here has got unique flora, unique. It's stunning and they're going to scrape it all up and . . . remove the beach for the length of the Sizewell C site which is quite large . . . and when we said, where are you going to store it then and how are you going to save the seeds and what are you going to do? They admitted freely last week that they had no answers to those questions.

From examining the actions of EDF during planning and commissioning, Janet and other concerned members of the public have come to understand that ecological safeguarding is not given as much precedence as the construction and regulation of nuclear power plants. This is encapsulated in the term "sacrifice zone": a physical space where the environment is degraded in order to bring about technological progression [385]. Such measures of compromised impacts for differing priorities and values are an example of the nuances of environmental politics. Prioritising certain matters over others is generally the case for many industrial projects, and indicates how the environment can in many ways suffer from the development and implementation of technology and innovation, one example being unnatural noise disruptions interfering with reproductive growth in marine habitats [386]. With plans for Sizewell C to be situated near the RSPB Minsmere[4] nature reserve, a variety of concerns have been raised over disruptions to coastal processes, wildlife disturbances, and impacts on air quality in the area, all of which threaten efforts to maintain ecological harmony [388].

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[4] The RSPB (Royal Society for the Protection of Birds) Minsmere coastal nature reserve is a SSSI focussed on bird conservation and management of various flora and fauna [387].

Alongside Janet's examples of land disturbances due to nuclear power, she also highlighted the absence of sustainable environmental arrangements for nuclear waste and the resulting irresolute nature of the nuclear industry. Her sentiments were shared by Pete, who claimed that:

> The UK have been dumping radioactive waste along with Holland and a few other countries, Belgium in particular, in the Atlantic since the 1950s. So we tried to stop that going ahead because there [were] fears about concentration of radioactivity in the marine environment. And it started to dawn on me that the Achilles heel of the nuclear industry is radioactive waste. They don't know what to do with it. They've never known what to do with it. The last thing you want to do with it is dump it in the ocean.

As Pete described, the nuclear industry's quandary over the disposal of high-level radioactive waste is an inevitable weakness that exemplifies the challenges of ensuring robust nuclear futures against rapidly changing environments. Furthermore, with the nuclear industry also drastically altering the landscape, the aggregated environmental changes are felt more strongly by the local population and nearby residents; on the drivers for her activism, Janet said: "habitat destruction is right at the top and along with that the noise and pollution and light and dust particles and all those negative sides", which was a viewpoint also shared by Pete; of the "invasive and unnecessary" infrastructural developments, Pete remarks:

> It is a beautiful area. It's tranquil and it's peaceful and to think that that peace and tranquillity is going to be disrupted by HGVs every few seconds going down that road, the lights and the pollution and the dust that's going to be created, the influx of all those people, it will transform it without any doubt whatsoever . . . it will transform this rural area into an industrial building site for a long period of time and it will urbanise it and that's what we don't want . . . essentially it's sort of, it's hallowed ground if you like and we're going to take 12 and a half million tons of equipment into this area, we're going to build this nuclear power station and there's going to be as a consequence, light, noise and dust pollution every day, most of the day and it's going to go on, not for a year or two but for 12 years.

In addressing the substantial scale of the project and its prolonged and extensive environmental disturbances on a sacred area, Pete outlined his heightened opposition to urbanisation and the destruction of beauty, tranquillity, and ultimately, the affective value of the area. Inasmuch as the construction of a nuclear power plant can transform an area, the environment itself can also transform the area around the power plant, and for Sizewell C, a specific environmental concern arises within the siting of the plant. Sizewell C is due to be situated next to the existing Sizewell B reactor on the Suffolk coastline, which has undergone shoreline erosion and accretion over the past few centuries [389]. Janet explained the significance of this in our interview:

> The sea has longshore drift so for years material is taken south, a spit is made and then at some time in a natural course of events that spit is wiped away and so it starts again. So this coast is known for its erosion, its drastic erosion specially [sic] in the winter when we get a north east wind and a high tide, that's the worst. And it's visible, you can go down, you can see it . . . and when you raise these points of the longshore drift, coastal erosion to . . . the EDF workers who are working for Sizewell C development, it's almost poo-pooed.

In addition to Janet perceiving her concerns over coastal erosion to be "poo-pooed", Pete noted EDF's persistence despite the environmental impracticalities highlighted by TASC as well as official bodies:

> We're looking at a 12 year building site being created on East Suffolk's coast on an eroding coast which is going to be-, in 100 years time it will be an island, Sizewell will be an island and that's not our figures, that's the Environment Agency. They acknowledge it's going to be an island. It just seems ridiculous or bordering on irresponsible to build a nuclear power station in that sort of location when all the predictions are that it's going to be surrounded by water within 100 years which is a blink of a biological eye in terms of nuclear power and nuclear waste.

By engaging in futures thinking and considering the environmental landscape of Sizewell one hundred years into the future, Pete is able to utilise these eco-futurisms and current knowledge of erosion processes in the area to draw attention to the "ridiculous" siting plans, highlighting how futures practices centre around present understandings, but also imaginative leaps into possible futures. Interviewee 7, much like Pete, also contemplated change over longer timescales, but did so in a retrospective manner, stating that "if you think about something like sea level rise and so on, the low level waste deposited in West Cumbria, nobody would have put that there now because it's an eroding coastline". In using hindsight to examine the nuclear industry's decisions, Interviewee 7 ultimately invites discussion around how future generations may view our environmental decisions, and whether armed with this intergenerational knowledge, equitable decisions can be made accordingly. In response to the concerns over coastline erosion at Sizewell, the Sizewell C media team released a blog post summarising their rationale over situating the plant next to Sizewell B. Accepting that coastal erosion is occurring in the area, they reason that Sizewell C will be "located on a more stable section of land", and that coastal monitoring and prediction will assist in the mitigation of flooding and coastal impacts [390], providing justification through their own nuclear futures endeavours.

As shown in this theme, many entanglements between nuclear power and the environment are intrinsic in the changing geographical landscapes and our changing socio-ecological relationships. Efforts to both reconcile and disconnect these entanglements have illustrated the complexities in establishing nuclear futures, as well as coming to terms with the nuclear industry's past ventures. In particular, the connections between the environmental impacts of nuclear power and society were expanded upon by Pete:

> I think nuclear power is part of that whole syndrome of not worrying too much about the impact of things because 'we've got bigger imperatives that drive us to do things like build nuclear power stations when the problems about nuclear power and health, well we're not really bothered about that. There are bigger things that we've got to do', and that's what's wrong in my view.

Here, Pete talked about the frequent diminishment of 'lesser' societal issues in order to justify the necessity of nuclear power, using the impacts of nuclear power on health as an example. As alluded to by Pete, there are complicated entanglements between nuclear processes and societal health, visible in the dichotomy of nuclear innovations—helping and harming. In medicine, radioisotopes are commonly used for diagnostic and treatment purposes, and are mostly sourced from fission reactors [391, 392]. On the other hand, radiation exposure due to environmental contamination from nuclear accidents may heighten certain health complications such as cancer risks; Christodouleas *et al.* detail this in their assessment of the health risks and the health benefits of nuclear power, writing that ^{131}I can accumulate in the thyroid gland once inside the body, emitting considerable quantities of beta radiation [393]. Touching upon this duality, Pete acknowledged that “isotopes are useful in medicine and those sorts of things”. However, he also spoke of the “vast areas of misunderstanding about exposure to radiation”. Citing increasing cancer rates in the population, Pete argued that contact between the environment and nuclear energy materialities creates problems relating to societal health. Indeed, on occupational health, Pete stressed that “we’ve got to be far more inventive about the way we create sustainable and healthy jobs. They’re certainly not healthy working in the nuclear industry as far as I’m concerned”. Additionally, he denounced uranium mining, declaring the increasing lung cancer rates, discarded uranium tailings [394], and its other impacts as “tragic”. In Pete’s view, the aggregated health problems arising from nuclear power activities cause uncertainties to emerge, particularly “unknown issues about low level radiation”. Janet voiced a similar view:

> So I mean it’s been things in this area again not made public like the . . . high number of cancers, leukaemias in the area but you can’t really get your hands on a proper study. The number of twins that are born in this area. There’s things like that going on that are in the back of your mind.

As Janet explained in her interview, where intuition and reasoning fuse together, doubts materialise over radiation and health consequences; this in turn can affect individual understandings of nuclear power and radiation. Similar to Janet and Pete, Interviewee 8 also perceived unknowns surrounding radiation and health:

> [Regarding Chernobyl, he remembered] . . . realising how fragile we all were really to the–, in both cases at the fragility of humanity to, what actually is quite a hidden–, you know radiation’s not something you can see you know, but it’s something that obviously when it happens, creates awful issues for people as well really. And so as a young person I was very much engaged in that real fear that came out of those issues really you know.

Here, Interviewee 8 spoke of how the ”hidden” issues of radiation influenced his initial understanding of nuclear materialities, and demonstrated how an unexpected nuclear event can significantly illuminate the intersections between radiation and mortality. The fragmented nature of his speech here, through the stopping and starting and sudden abrupt ends, also evidence the emotionally-charged nature of this topic for Interviewee 8. He described how accident materialities became a significant concern, particularly during childhood:

> I've always been concerned about the accident element of nuclear power and what if things go wrong. Probably my interest really started ... with the Chernobyl accident happening [in] 1986. I was 14 at the time and I really remember how vividly the impact of that was. And then later on, you know particularly working with Hiroshima and that I started to obviously realise so many people that get affected by nuclear materials.

Calling on the power of memory, Interviewee 8 was explicit in attributing the safety issues associated with nuclear technologies as a driver for his anti-nuclear activism, noting the "danger" and "risk that nuclear power has within it". Elaborating on the risk inherent in using nuclear technologies, Interviewee 8 spoke in detail about risk potentialities, placing emphasis on the prolonged lifetime of radioactive isotopes:

> ... mistakes can happen, accidents can happen, malicious incidents can happen and so forth and if there is an accident with nuclear it's a bit bigger than if it's other things really. I mean chemicals, explosions are a big deal but you know, generally the impact is there and it's done whereas the other element with nuclear is that the radiation can stay around really and it can create a longer term issue and longer term contamination as well.

As shown in the comments made by Interviewee 8, perspectives can be particularly important in the context of public safety, where uncertainties inform risks and regulations. According to Stoutenborough, Sturgess, and Vedlitz, the Fukushima Daiichi accident "killed any momentum the nuclear industry had gained", and had "resulted from insufficient safety regulations in Japan, a problem that does not exist in the United States" [395]. Their locational comparison of safety regulations is intriguingly definitive, and imply a degree of dependent faultlessness, which Interviewee 8 disagrees with when he claimed that "Japan has one of the most advanced and before that safest nuclear systems in the world. So if it can happen in Fukushima, it can happen anywhere in the world".

Interviewee 7 focussed on regulatory decisions regarding safety and the knowledge gained after the Fukushima Daiichi accident:

> I would assume Japan is a modern country that has a good regulator and that if the power stations are open again then that means that the regulator's happy that they're operating safely and they've learned the lessons from what happened at Fukushima. But maybe that's naïve of me to think that. But you know it caused ramifications for nuclear power generation in the UK as well.

To this, he referred to the "Weightman Report" from the Office for Nuclear Regulation, which details recommendations for safety improvements in the UK's nuclear industry after observing the impacts after the Fukushima Daiichi accident [396]. The report states that there are no significant weaknesses in the UK's nuclear industry. However, there is a need to improve facilities and operations after the lessons learned from the accident. The need for improvements and adjustments to policy and management is particularly pertinent considering previous instances of malpractice in the nuclear industry, such as the cover-up of potential safety issues at the Fukushima Daiichi power plant in the years preceding the accident in an attempt to avoid disrupting operations [397].

Safety has been understood as an "ethical dilemma" of nuclear power; Uddin examines the conjectural adoption of nuclear power in Bangladesh through the proposal for countries in the Global North, responsible for 92% of global carbon emissions [398], to share nuclear energy technologies with countries in the Global South, which disproportionately bear the resulting effects of emissions-driven climate change [399]. In assessing Bangladesh's ability to incorporate nuclear power into its energy mix, Uddin concludes that renewables are needed above all to manage the energy crisis as "Bangladesh has a low capacity to maintain nuclear power plants and is unable to provide for the safety of its citizens", and that a global regulatory committee must be established in order to uphold the security of nuclear technologies.

Interviewee 8, when reflecting upon the destructive capacities of nuclear weapons, remarked that "there are still thirteen thousand nuclear weapons in this world and it only takes one of them to destroy a city", and that "the vast majority of people now have moved from the rural areas into the cities, so an attack on a city would be so much more devastating". For Interviewee 8, in addition to the ever-present threat of nuclear weapons, there is a large amount of dependency placed upon decision-making and technological control, critically increasing the possibility for a significant consequence to occur. As an example of this, Vasili Arkhipov is considered to have prevented World War III by being the sole Soviet officer on board a submarine to refuse the launch of a nuclear torpedo at a US destroyer [400]. However, malicious actors with nefarious intentions, such as terrorists, might wield high-risk nuclear technologies differently. Wirz and Egger surmise that although a nuclear terrorist attack is "very unlikely" as there are many barriers preventing terrorists to obtain a nuclear weapon, most countries are ill-prepared for the event of such an attack by a highly-organised terrorist group in terms of contingency plans [401]. Interestingly, Jenkins claims that terrorist organisations are drawn to the connotations of fear that the term "nuclear" brings, rather than the actual use of nuclear materials to bring about mass casualties, which could inform the nuclear industry's developments over the coming decades [402]. Kristin explained how physical plant security implementations were "largely fear based", which was substantiated by Heather's description of the security measures at the Diablo Canyon Power Plant in California, where Kristin and Heather both work:

> We have physical security guards with guns and we have lots of fences, lots of razor wire, lots of concrete, lots of you know barriers for like anyone who might be trying to run in and there's delay tactics, you know like fences and gates between certain pieces of more vital equipment and there's a field of boulders so that people can't walk through 'cause it's like they'll twist their ankle and there's just like towers and like gun turrets and it's just like yeah it's kind of ridiculous how much there is and how unnecessary it probably is. Because anyone who would try and get into the plant or do anything, the impacts would be so minimal.

Heather, in detailing the extensive physical deterrents at Diablo Canyon, helped to illustrate the efforts taken by the nuclear industry to considerably mitigate any external risk factors, despite the fact that adverse incidents are unlikely. In contrast, for internal risks at nuclear power plants, such as infrastructural failures leading to a nuclear accident, different measures are required to appropriately reflect the nature and scale of the risk. However, Openshaw discusses the inability for a nuclear power plant to guarantee absolute safety in spite of any appearance of safety, stating that "insufficient time has passed to be even certain that major accidents are indeed going to be very rare and unlikely events" [403]. Openshaw also calls attention to the uniqueness of a nuclear accident, adding that there is "no obvious upper limit" on the numbers of casualties or compensatory value for accidents. At the crux of the matter, Openshaw determines that "human nature is fallible", a phenomenon that Interviewee 8 also observed:

> Mistakes happen, you know. You know, can you completely stop accidents? I've not seen any evidence you can really. In any technology, not just nuclear. Speaking as a [planning officer] that used to do risk assessments all the time, you know if you'd have asked me ten years ago that you get a COVID pandemic that would last 15 months and kill millions of people, we certainly had risk assessments to say that but we didn't expect it to happen in the way it did ... it's impossible to completely get risk out of the equation really, you know. The world is a risky place, it will always remain so really, you know. Things happen and technology might be able to iron out some of that but it's very difficult to say it can completely iron out that really, you know.

Interviewee 8's observations around human-led technologies and the uncertainties of the future highlighted the impossibility of designing truly faultless systems, and he emphasised the limitations of technological safety advances. For the development of new nuclear technologies, the critical safety assessments warranted due to any unexpected risks can therefore always be deemed as insufficient, informing how large-scale nuclear technologies – such as fusion – are managed. For nuclear fusion in particular, Lukacs and Williams found similarities between the safety issues of fusion and fission technologies – the removal of decay heat from activated materials after shutdown of the fusion process in a LOCA, hydrogen explosions, and external hazards such as natural disasters, amongst others [404]. However, they stress that robust data on fusion failure rates are missing, and that safety standards for fission reactors cannot be directly applied to fusion reactors, highlighting a need to develop and adopt a fusion-focussed safety standards framework.

Interviewee 5 discussed the challenges of promoting fusion technologies given the preconceptions arising from the conflation of fission and fusion and the resulting associations, stating that “it is up to us in that information campaign to stress that there [are] inherent safety advantages. The waste you produce won’t last as long, won’t be as active as you get with fission”. By needing to leverage the safety advantages of fusion reactors to garner trust in fusion, this demonstrates the inevitable comparisons made between the safety of any new technologies to existing and established technologies, and speaks to the influence that public concerns and scrutiny hold over technological development and new innovations. On Fukushima Daiichi being an “old plant”, Interviewee 5 claimed that “newer stations are more inherently safe. They shut down much more quickly. You don’t have enough fuel or residual heat in the process for a runaway anymore”. However, Interviewee 8 contextualised the safety of new technologies with respect to former incidents involving their predecessors, stating: “you can devise every technological device … to say it’s all going to be safe, but you’ve still got the issue that it’s happened in the past and humans are frail beings as well”.

Pete was in agreement with Interviewee 8, and emphasised the safety risks inherent in nuclear reactors in the UK by extending the generally unprecedented nature of accidents to the UK reactors, envisioning the devastation:

> God forbid if there were ever to be an accident on the scale of Chernobyl or on the scale of Fukushima or whatever it might be and I know that the conditions are different … but we have to remember that all accidents are unforeseen.

He continued, cautioning that in the case of an accident occurring, “we would have a situation where the emergency plans in place would be seen to be inadequate”, referencing the 30 km limit of the extended emergency zone around the Sizewell plants. Janet, who lives in the vicinity of the Sizewell reactors, also deemed the emergency evacuation procedures insufficient, stating that:

> I am quite alarmed we’ve never had a practice, never had a practice. It’s been

> raised time and time again about the need to do that. We only go as far as Leiston and that feels it's not far enough away.

For Janet, and others who are local to the area, the nature and scale of the risks necessitate the trialling of any evacuation procedures, which may provide some degree of confidence over the safety operations in place at the Sizewell plants in preparation for – and anticipation of – an accident. For other interviewees, nuclear accidents heralded the ability for reactor safety, and plant risk levels, to change. For example, Wade reasoned that although previous nuclear accidents had occurred, other factors were in effect, such as human and design errors:

> The Three Mile Island disaster was not a disaster. Nobody died there. But that was caused by bad instrumentation. People didn't know what was going on and people learnt from that ... Chernobyl, they were being unsafe. The design was bad and the people operating the plant didn't know what they were doing and they decided to override all the safety things and it was unsafe anyway. And Fukushima was caused by a tsunami but ... only one of the nuclear plants in Japan had trouble and that was because the emergency generators were down below the nuclear plant rather than on the hill up behind where they would have been safe from the tsunami. So that was just planning.

Wade's assertion that the Three Mile Island accident "was not a disaster" demonstrated the significance of associating safety and risk with linguistic distinctions, especially colloquially. Despite previous occurrences of nuclear accidents, Wade maintained that nuclear power "[is] incredibly safe". The safety of nuclear power was also mentioned by Interviewee 6 in her message for a future generation; she wanted to pass on "that it's safe, that it's reliable, that the stations are run by incredibly skilled professionals that take their roles incredibly seriously and are incredibly well trained at what they do". The assurances of the trustworthiness of the nuclear power plant operators suggest feelings of protection and security in the context of past reactor incidents, and a sense of the overall state of preparedness of the nuclear industry.

Some interviewees, such as Pete, felt that reactor technology "is too complicated" and that "we've got to eschew it and make sure that we go with technologies that we can understand, that we can control and that don't have huge consequences if they go wrong. Which sadly you can't say about nuclear power". Interviewee 8 shared views similar to Pete's; he spoke of the critical safety potentialities that accompany complicated reactor technology:

> With such complicated machinery there's always a possibility something goes wrong. If you look at what's happening in Flamanville and Olkiluoto, which are identical reactors, they're both years behind schedule, billions over budget and mainly because they've got safety issues with them.

Later in the interview, he commented on the eventual material failure of plant infrastructures and technologies:

> The concern of an accident comes out of that age really, that degradation really and something going wrong because, simply not because of human error, just because it's just, you know the parts don't work very well really. Now I know regulators work very very hard to try to ensure that doesn't happen and so far touch wood we haven't had that but we've come very close to it sometimes as well.

In particular, Pete considered the safety issues of complicated nuclear technologies as motivation for steering away from the reliance on nuclear power and towards renewables, reasoning that "we're going in for these really complicated, potentially dangerous types of technology when there's more energy falling per square metres on the earth's surface than we can ever possibly use". Pete speculated that as a result, "there will be far more jobs and there will be far more safer jobs and they would be far more permanent jobs if we went through to a renewables programme rather than a nuclear based one", calling attention to the considerable social impacts that arise from energy policy decisions. It is interesting to note that Pete's comment leans into a nuclear power versus renewables narrative, compared to the low carbon (nuclear power and renewables) versus high carbon (fossil fuels) narrative. This isolation of nuclear power as an oppositional rationalisation is important in that the framing of perspectives can lend credence to and amplify, in many ways, contradictory narratives.

Certainly, the comparisons between nuclear power and other forms of energy generation has provoked much discussion around the role it may take in energy futures. One common comparison that has been made is with renewable energy:

energy that is generated from renewable resources such as wind, solar, geothermal, and hydroelectric power, producing no greenhouse gases in the process and negating the use of finite fossil fuel resources. In the UK, renewable energy was responsible for 39.9% of the nation's electricity generation over a period of 3 months in 2021 [405]. In 2020, countries such as Paraguay and Iceland generated 100% of their country's power from renewable sources, mainly hydropower, with several other countries such as New Zealand, Brazil, and Greenland also possessing a large majority of renewable energy shares, with many other countries gradually increasing their shares over the past decade [406]. The increased reliance on renewables is generally strongly supported due to their relatively inoffensive nature and a considerable societal acceptance of renewable energy—this shows how relatively expected histories i.e. the absence of large-scale deleterious events, play a part in the narratives of renewable energy technologies. This relates in particular to one of the key arguments of this thesis: that narratives matter a great deal when constructing perspectives of energy materialities.

Both renewable and nuclear technologies are currently involved in the transition from finite, highly polluting energy sources towards "clean" low-carbon energy generation [407], and have ignited much discussion over whether their relationship is competitive or cooperative. In 2017, the South Korean government initiated a decreased reliance on nuclear power usage, and instead increased the usage of renewable technologies, which were found to have greater economic effects than that of nuclear energy [408]. Park's study in South Korea found that there was a tendency for people who identified with ethics and concern for future generations to prefer renewable energy over nuclear power [409]. However, the complete replacement of nuclear power with renewable energy in South Korea was also found to be unfeasible [409]. Verbruggen argues that there exists an antagonistic relationship between nuclear power and renewable energy, and reasons that nuclear power shares "no common future" with renewable energy [410] due to many factors such as differences in risk levels as well as resource usage. Sovacool also questions the necessity of nuclear power in framing renewables as more effective at reducing carbon emissions, citing the rising decommissioning and storage costs of nuclear power, as well as the vast quantity of water required for the plants, as arguments for the proliferation of renewables and the diminished role that nuclear power should play in the future energy mix [411, 412]; some claims, however, have been invalidated by alternative analyses [413]. Contrastingly, a collaborative relationship between the two technologies can take the form of nuclear-renewable hybrid energy systems in an energy mix, proposed for commercialisation but requiring further conceptualisation [414–416].

From their low energy efficiency, to their reliance on dynamic weather patterns that produce non-continuous periods of electricity generation [417], renewables have their drawbacks, as is the case with every form of energy generation. However, the social and ecological impacts of renewable energy have brought to the fore many of its complexities [418–420]. In Norway, Indigenous Sámi reindeer herders faced threats from wind farms on the Fosen peninsula as they encroached on reindeer grazing regions, disrupting their culture and livelihoods [421–423]. In the Global South, for countries such as Kenya, land contamination from the leaching of rare earth metals found in solar panel e-waste such as lead and mercury has highlighted issues in ensuring a sustainable end-of-life for solar panels [424, 425].

The relativity of risks, hazards, and problems of renewables and nuclear power are also regularly discussed relative to those of fossil fuel sources; the rate of certain greenhouse gas emissions in OECD countries increases with non-renewable energy sources relative to that of renewables [426], and nuclear power was calculated to have caused over 97% fewer deaths than coal and gas [427–430]. By analysing various methods of energy generation through perspectives, the social costs and value of these methods are able to be dissected further than solely as individual parts in the wider energy landscape of the present and possible futures.

Considering the absence of prompts pertaining to renewable energy in my interview questions, the emergence of this topic in the interviewees' responses highlights its tether to nuclear power and their similar roles as fossil fuel alternatives in the energy mix. Interviewee 7, in declaring that "it's not one solution or the other" when it came to "a very complex and evolving energy mix," raised the issue of selective decarbonisation: "all we've done so far is decarbonise about 40% of the 20% of our energy that's electricity. We haven't decarbonised heat, we haven't decarbonised transport, so we need to do all of that". Given the multitude of societal and technological entanglements, the employment of both renewable technologies and nuclear power has been of interest to stakeholders in the energy sector in managing energy futures.

Generally, opinions of renewable energy with respect to nuclear power ranged from direct opposition to either technology, to embracing a shared cooperative relationship between the two. As an example of the former, Wade proclaimed to be "very strongly against renewables", and in his message to future generations, he wished to:

> . . . apologise for the waste of money and effort that has gone into renewables because that is a complete and utter waste of time. They're unreliable, they won't work reliably. There are big breaks in availability. They destroy nature and I would feel I would have to apologise for that because I allowed it to happen.

Adopting an apologetic stance, Wade's polemical comment on renewables reflected on how 'allowing' the pursuit of renewable energy becomes, to an extent, a personal responsibility amid a recognition of our societal power and ability to influence energy discourse. To a lesser degree, Interviewee 5 spoke of his vision of a shared role for renewables in the energy mix, reckoning that "you can't in any great conscience rely on renewables to do it all," explaining that "nuclear should have a very key role in a carbon free future as well as fusion, as well as renewables". On this, he clarified:

> To envisage that renewables around the world does it all is untenable in terms of energy storage, in terms of transient nature. I mean we've got lovely … beautiful blue skies here, nice and warm but absolutely no wind. I'm looking out the window now and hardly a breath of wind. I was up in Scotland actually, drove past Lancaster last week twice. At least half the turbines that are up there weren't turning at all. Now that's not to say I'm anti-renewable. Renewables clearly have a key role but for those that say they will do everything then it's just not tenable.

Interestingly, Interviewee 5 surmised that certain pro-environmentalist groups would argue for the sole use of renewables, stating that "Extinction Rebellion, Friends of the Earth, the green lobby … would probably know what fusion is but still be sceptical because it's going to take too long to deliver and that renewables should do everything". In the same vein, Interviewee 6 cites George Monbiot as an epitomisation of an alternative movement within pro-environmentalist groups—encouraging the utilisation of nuclear power, and specifically its timescales, to 'enable' the growth of renewable energy technologies:

> You have got some fairly vocal writers like George Monbiot who have changed their stance over the years. They've realised that actually nuclear has got an important role to play in replacing fossil fuels in helping us reach net zero and enabling more renewables to come online. That it's not one or the other but actually it's really important that we have more renewables and to do that we need more baseload reliable low carbon energy and that's what nuclear delivers. That kind of you know reliable, dependable baseload that you need on the system to enable more renewables to come online.

Speaking on their shared role, Interviewee 6 argued that the expansion of renewable energy necessitates the use of nuclear power in its role as a bridge for a low carbon future. She provided more detail in describing an ideal energy mix:

> I think we need more renewables. I think you know potentially how it would shape up percentage wise, you'd have potentially 60% renewables and maybe 30%, up to 30% nuclear and then the rest kind of gas, battery whatever to fill that kind of gap. But I think it has to be part of the mix.

In quantitatively describing the possible energy shares of each method of energy generation, Interviewee 6 envisioned renewables as a majority contributor and suggested a quantifiable limit for nuclear sources. Given the ambiguity in her insight as to whether she alluded to a near or far future, her mention of the prospective use of gas could imply its gradual phasing out, or its continued—but hugely decreased—role in the energy mix, highlighting our deep-rooted dependence on fossil fuels. Kristin also touched on the current requirement for fossil fuel supplementation, her main argument centering around its succession with nuclear energy to ensure reliability and energy security:

> Other types of clean energy still are going to play a role and do need to play a role so we can decarbonise even more but nuclear's such a critical backbone you know with its ability to provide 24 hour a day clean electricity that so many other sources fall short and that's where we end up blocking in reliance on fossil fuels currently.

Pete, however, disagreed; instead, he thought it was "much better to deploy quickly deployable, renewables right now which are cheaper and far more effective," in order to "fill the gap ... which we're doing apace because there's nothing else that's going on". He also reasoned that "we've got to deploy more renewables and we've got to drive down demand and I think nuclear power will be seen to be redundant". In his adamance towards changing societal practices to negate the need for nuclear energy, he also viewed the mechanisms and methods of nuclear power as complex:

> I don't understand why we're so fixated on complicated technology. You know, it's very straightforward. The sun shines, you capture the heat from the sun and you kind of catch the ambient energy and heat in the atmosphere and we have the technology to be able to do that. There is more energy falling per square metre on the earth's surface than we can ever possibly use and yet we don't use it. And I don't understand why we have to be so technological about things when the simple ways of meeting our energy demands are all around us.

Here, Pete's commentary on "complicated" and "straightforward" technologies was also a characterisation of passive and non-passive energy sources; requirements for uranium enrichment and lengthy and detailed commissioning and decommissioning involve a higher level of cultural and sociopolitical entanglements, compared with renewable energy sources such as solar energy. The equation of simplicity with positivity and safety, and complexity with negativity and risk, is interesting to note here in Pete's comment, as it gives an insight into the psychological categorisations that occur with nuclear power technologies. A similar sentiment was expressed by Interviewee 8, who stated:

> Renewables are a third of the cost of nuclear at the moment on current prices. They are coming in quicker and quicker, they're getting more and more technically efficient as well. They're easier to deploy, much easier to deploy than Hinckley C for example and they can be done quicker and the thing is, the climate emergency requires you to make quick decisions and quick solutions and the problem for nuclear remains. It's slow, it can't be done quickly, it's got to go through all these safety hoops in order to get things done.

Interviewee 8, in arguing that the urgency of the "climate emergency" demanded rapid technological deployment, emphasised the relative feasibility of renewable energy compared with that of nuclear power, using Hinkley Point C as a specific reference. Hinkley Point C has been in construction since 2017, and EDF Energy claims that the plant will generate electricity for 60 years [431]. Beset by cost revisions and scheduling delays from political and economic conflicts as well as the COVID-19 pandemic, Hinkley Point C's factors of resistance were used by Interviewee 8 to illustrate the time-pressured frictions that arise from uncertain entanglements with situational drivers, rendering nuclear energy unable to deliver essential action in a short time frame in order to steer away from catastrophic futures. This led on to Interviewee 8 declaring that "the philosophical point of view [is] that renewables is the way forward really," indicating a moral undercurrent inherent in the renewable energy narrative.

In contrast to Pete and Interviewee 8, Janet held a slightly more balanced understanding of renewable technologies, in expressing "I know there's pros and cons for wind power too with the birds' destruction and what have you". However, this statement was a preface for Janet's thoughts on renewable technologies, wherein she articulated similar sentiments to Interviewee 8; she advocated for the usage of time and resources to instead support the implementation of renewables: "I feel we're missing a trick with tidal power. We haven't explored solar power enough," such investigations are accessed by pushing the boundaries of renewable energy technologies and progressing into its undiscovered avenues in current research [432–434].

It is clear that renewable energy, much like nuclear power, is a polarising subject. In these interviews, the views encountered when discussing renewables and nuclear power varied hugely between each interviewee, but were essentially all centred around energy security for the future. In transitioning towards low-carbon energy generation, both renewable energy and nuclear power are playing significant roles in realising these futures. In a 2021 YouGov survey, 65% of UK adults surveyed (n=3071) expressed support for nuclear power to be part of Britain's energy mix; within this, 34% of people claimed that nuclear energy should play a major role [435]. With the UK government giving its approval and support to both nuclear and renewable energy projects [436], the path shared by renewable energy and nuclear power is continuing to be defined and shaped by our societal attitudes and evaluations, and will be part of many conversations surrounding the energy mix in the years to come.

3.5.2 Fukushima Daiichi: a case study

At 2:46pm, a magnitude 9.0 earthquake caused a devastating tsunami to hit the north-eastern coastal regions of Japan on 11th March 2011 [437]. Various infrastructures suffered vast amounts of damage from the tsunami—the waves of which reached 40 metres in height—and around 500,000 people were displaced from their homes from the destruction, with over 17,000 fatalities [438]. The Great East Japan Earthquake not only impacted the lives of the citizens of Japan, it also had profound effects on their social and material relationships, largely amplified by the accident at the local nuclear power plant [439].

The Fukushima Daiichi power plant, which is currently being decommissioned, is situated on the coast of Ōkuma, in Fukushima, and managed by the government-owned Tokyo Electric Power Company (TEPCO). The plant consisted of six Boiling Water Reactors (BWRs), where light water is used as both a coolant and a neutron moderator in a one-cycle flow system in which it cools the reactor core and also turns the turbine blades. During the earthquake and tsunami, considerable damage was caused to the Fukushima Daiichi nuclear power plant; the power supply lines were damaged by the earthquake, and the backup diesel generators were flooded, rendering them inoperational and causing a total power outage at the plant. With the absence of power to the coolant pumps, the cooling water that was required to remove the excess heat from the fission reactions could no longer be circulated around the fuel, and was instead heated by heat decaying from the fuel. With the cooling water depleting as it boiled into steam, the core became progressively exposed, and the pressure inside the reactor vessel increased. The temperature of the fuel climbed rapidly and melted in the absence of any significant heat exchange. Zircaloy cladding generally reacts very little with water, but generates hydrogen upon reacting with steam. In Units 1, 3, and 4, hydrogen accumulated in the reactor buildings and eventually ignited in air, leading to hydrogen explosions that ruptured the containment of the reactor and the release of radioactive isotopes into the surrounding environment [440, 441].

In the immediate aftermath, the Japanese authorities ordered the evacuation of residents in a 20 km radius in response to the spread of radiation from the reactor. The International Atomic Energy Agency (IAEA) found that officials were unprepared for an accident of this scale due to assuming the seemingly unquestionable high degree of safety of Japanese nuclear power plants [437]. In understanding that drinking contaminated milk after the Chernobyl accident brought about many more cancer cases in the population, food measurements quickly began to take place [442]. Products such as vegetables were found to contain significant levels of radionuclides, including iodine-131, caesium-134, and caesium-137 that exceeded the regulatory limit imposed by the Japanese authorities [443]. Further analysis of food product measurements by Merz, Shozugawa, and Steinhauser found that contamination with caesium-137 was detected more in animal products, and strontium-90 for vegetable products [444]. In Fukushima and beyond, the elemental changes in food—an augmentation of a human need for survival, generated a fundamental disturbance in society's relationships with the material and biological world, leading to the anxiety and uncertainty observed amongst many members of Japanese society after the accident.

A similar sense of disruption was applied to the contamination of land and infrastructure, with damaging effects on livestock and agricultural farming [445]. Large areas of surrounding soil were contaminated with caesium-137, possessing a half-life of 30.1 years and adsorbing to soil, clay, and plant matter [446]. This constituted dangers to environmental and biological health, as animals and humans who eat the contaminated vegetation would ingest the radiocaesium, exposing their internal organs to ionising radiation [447]. Naturally, this devastated much of the agricultural industry in Fukushima, and farmers who relied on crop growing for their livelihoods suffered enormous losses to their businesses from this contamination, in combination with public fears and stigmatisation over the radiation in their products. A significant removal effort was conducted by the government, in which 5 cm of topsoil was collected in large black sacks [448], and in 2015, transported to a temporary storage facility in the towns of Futaba and Ōkuma, where it is estimated to eventually hold around 14 million m^3 of the contaminated clay [449, 450]. The areas where removal of contaminated soil took place were then substituted with less fertile crushed granite. This caused issues with plant growth, and drove more farmers to adopt greenhouse growing techniques that inhibited the uptake of caesium-137, as well as using technology to adapt to the circumstances—for example, using remote-control farming for water regulation in rice paddies [451]. Considering the substantial decrease of 30,000 farmers in the region since the accident, reviving the farming speciality in the prefecture by incorporating technological aids to assist with monitoring radiation and remote farming has helped to restore many of the cultural and community practices once seen in the area as well as enabling farmers to reclaim their land [452].

As the Japanese population grappled with the unfolding of events, trust in Japanese authorities diminished sharply as conflicting and incomplete information was released to the public through media channels. Information was released too late, allowing confusion and misinformation to spread on social media and causing public confidence to plummet [453]. Just one day after Fukushima, a group of individuals founded a citizen science initiative for radiation monitoring as an answer to the inadequate dissemination of information: 'Safecast' [41]. The organisation enabled open access to accurate and updated radiation tracking, in the form of figures, maps, and trends. This was made possible by taking radioactivity measurements using the 'bGeigie Nano', a "mobile, GPS enabled, logging, radiation sensor" resembling a Japanese bento lunch box [454], housing a modern Geiger-Müller (G-M) counter and communication parts [455]. The communality of these bGeigie Nanos was especially pertinent during shortages of G-M counters; the supply of domestic G-M counters dwindled over widespread 'panic buying' and avoidance of Chinese-manufactured G-M counters [456], and it was widely believed that the authorities "withheld information" [457]. In the years succeeding the initial operation of Safecast, the intersection of 'apolitical' data from citizen science and data from 'official' sources has both foregrounded the role that the public can play in collaborative research and provided an alternative avenue of information, which can both supplant and reinforce political data and institutions [458]. In this way, Safecast can be regarded as a counterpoint technology that is trusted, compared to nuclear power which is an example for some of a distrusted technology, likely due to perceptions as a technology of 'the people'. Overall, the use of technology in more closely connecting materials and society, as seen with Safecast, also allows for distance to be safely maintained whilst providing allegedly unbiased certainty and assurance. Since their conception, Safecast has expanded upon the monitoring of environmental contaminants, developing air pollution monitoring devices, allowing for bodily autonomy to be furthered by access to knowledge and enabling exact awareness of the environments lived in and experienced by many, just as they did in the aftermath of the Fukushima Daiichi accident.

Additionally, the growing distrust in the government was found to have triggered symptoms of psychological distress in the public, magnifying concern for long-term mental health difficulties in the general population [459]. Years after the nuclear disaster, many residents and workers involved with the Fukushima Daiichi plant were found to struggle with high levels of anxiety and psychological, post-traumatic stress, from the disaster and the subsequent evacuation [460, 461]. The phenomenon of 'genpatsu rikon', or 'atomic divorce', arose due to the familial strain of evacuating homes and through disagreements on radiation safety between married couples. Women, especially mothers, tended to be "voluntary evacuees" who left the prefecture with children and other family members due to concerns over radiation, whilst their partners, who were usually men, tended to remain in the family home near the site of the disaster [460]. People associated with the nuclear accident faced discrimination, such as children from Fukushima encountering school bullying after evacuating [462], and the livelihoods of farmers and fishermen from the prefecture were in turmoil after general avoidance of their products over concerns with their radioactivity levels and safety [463]. Gender-based discrimination was also prevalent after the accident. Haworth reports that Fukushima women are viewed as "damaged goods", and are held in disdain over the perceived impairment of their reproductive 'responsibilities' [464]. Similarly, Makino discusses the infantilisation of evacuated women, who were derided over their concerns over radiation, as well as the societal pressure for men to "man up" and "protect their hometowns" by remaining instead of evacuating [465]. Evidently, the radiation that became suddenly embedded in various aspects of society engendered significant attitude shifts that altered social-material relationships, marking just one dimension of the human toll of the nuclear disaster.

The accident has enabled researchers to investigate the acceptance and social role of nuclear power in Japan and beyond. Kato's review of economic incentives and citizen attitudes around the accident explains how the 'bribery effect' appears in compensating local residents of nuclear power plants to balance risks; utility bill refunds were the more favourable form of compensation than upgrading local infrastructure, but, perceptions of these benefits declined and improved respectively after the accident [466]. Institutional trust amongst Japanese university students underwent a dramatic decrease after the accident, with women found to fear radioactive contamination more than men [467], and in Italy, citizens tended to adopt more pro-environmentalist values after the disaster which were signalled by a change in increased concern for altruistic values such as human and environmental welfare [468]. Attitude shifts in Germany, where the government decided to phase out its existing nuclear plants, were found to be drastic: the proportion of the population opposing the continuation and advancement of nuclear power in Germany increased from 31% in 2010 to a majority of 73% after the Fukushima Daiichi accident [469]. Holding a similar outlook to Germany, the Swiss government decided in 2011 to phase out nuclear power after the nuclear disaster [470]. Siegrist, Sütterlin, and Keller identified the phenomenon of "Schweigespirale", or "spirals of silence" in the German- and French-speaking populations of Switzerland [40, 471]. As opposition to nuclear power became the dominant viewpoint, benefit perception of nuclear power decreased due to the absence of industry and political support. Moreover, proponents of nuclear power felt unable to voice their support, and these became negative feedback loops. Contrastingly, Capstick *et al.* report on the unexpected 'resilience' of British public attitudes two years after the Fukushima Daiichi accident, noting that there were no significant shifts in public concerns towards nuclear power, furthermore suggesting that opponents of nuclear power became increasingly ambivalent or uncertain [472], possibly due to other societal drivers taking precedence, such as political or economic events, or geographical distance. Given that the accident elicited affective and cross-national attitude shifts, it was of interest to gauge the interviewees' perspectives and their understanding of the devastation in Fukushima in order to gain more insight into how it contributes to their personal nuclear narratives.

For the interviewees, the Fukushima Daiichi accident became a signifier of the outcomes of atomic power, an array of different representations of nuclear power technologies and the eventual societal impacts. Patterns arose in the adjectives used to describe the accident in the interviewees' responses irrespective of view: "terrible", "dreadful", "devastating", creating affective links to the severity and scale of the disaster. They spoke widely on the materialities of the accident in conjunction with its emerging issues, and shared their interpretations on these material social connections. Interviewee 7 remarked that "[the accident] wasn't a Chernobyl in terms of risk or damage to the environment", drawing up the emotional and material associations of Chernobyl as a marker of extremity and in the process slightly diminishing the instinctual emotional reaction to the incident. Similarly, Interviewee 5 noted the fortified structure of the buildings at Fukushima Daiichi: "there's obviously been a lot of issues there but in terms of actual health and safety the plant stood up to a once in a lifetime, you know once in a thousand year event incredibly well actually". The sturdiness of the reactor and its buildings is foregrounded here alongside the infrequency of the disaster, bolstering the viewpoint of Interviewee 5 who regarded the accident as a testament to the resilience of the power plant. He continued: "Fukushima didn't damage the nuclear industry and in a way it strengthened it because it stood up to an event it was never designed to stand up to and nothing directly catastrophic has happened". Interviewee 5's statement informs us of his view of risk and benefit: the Fukushima Daiichi accident had a catastrophic impact on many people's lives, as mentioned earlier when referring to the psychological distress and discrimination of those living near to the nuclear power plant, but for Interviewee 5, the only catastrophic aspect of the disaster was loss of life, and not the effects and consequences for those who have been indirectly affected by radiation. Holding a similar view regarding the recovery of support for nuclear power, Interviewee 7 stated: "it always takes a dent when something like Fukushima happens but then it does seem to recover and climate change has maybe pushed up support for nuclear to some degree". The recovery of trust in the nuclear industry due to Fukushima Daiichi follows specific avenues of reasoning and thought, where the containment and management of radioactive material was involved with disaster mitigation. The language used here indicates how nuclear specialists view nuclear accidents in a temporal context as one-off unforeseeable disasters, rather than as ongoing risks. However, interviewees 5 and 7 have omitted the physical and psychological 'radioactive burdens'[5] that arise from a nuclear incident, especially borne by citizens directly affected by the event. In characterising our interactions with materials as separate to our corporeal relationships with nuclear power, we risk obscuring the intimacies and sentiments attached to atomic energy, which form the foundations of human-material interplay in nuclear futures through the experiences of citizens, actions of plant workers, building materials, and reactor design.

Pete, on the other hand, considered the official and immediate response from governments and officials to be an attempt to establish a narrative early on:

> The interesting thing for me was as soon as Fukushima happened, the government here brought together all the heads of departments and the immediate response was, it doesn't affect our nuclear programme. They made sure that they nipped the whole thing in the bud very very quickly and made sure that the public was aware that the government thought that it was something that happened in Japan because of a tsunami. It wouldn't happen here. We are much better equipped to deal with things like that because we have a resilience programme etcetera etcetera, and therefore the nuclear programme marches on. They reacted very differently in Germany.

By contrasting the actions of the UK and German governments in suppressing public alarm, Pete illustrated the differences between the outcomes of a nuclear accident in the very different pathways that the two countries took after Fukushima Daiichi: whereas the UK government made sure to accentuate the impact of the

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[5] I use 'radioactive burdens' here to encompass the extensive efforts that have to be undertaken by people affected by the radiation from a nuclear accident. Whether this is consistently monitoring the radioactivity of their food intake, or excessively worrying about the spread of radiation in the environment, the act of being persistently entangled with abnormal levels of radioactivity takes a toll on affected citizens and would constitute the 'radioactive burden'.

natural disaster on the accident in an effort to establish continuation, the German government made their decisions partly based on admissions of uncertainty that are seemingly in opposition to the reasoning the UK government uses to retain its nuclear programme. There is seemingly a relation between the unchanged attitudes towards nuclear power after the accident as reported by Capstick *et al.* [472] and the actions of the UK government in this instance, in taking an early and clear control of the narrative. Significantly, in his use of the phrase "marches on", Pete represents this programme as an almost ceaseless procession that maintains progress when public concerns have been assuaged, which are often laced with personal meanings and emotions. In particular, Janet attached her own emotions to the accident, having felt "all those human concerns that one would feel for the people living there and [hoping] desperately it would never happen here". In this way, by tracing the scale of the Fukushima Daiichi accident to her surroundings, Janet's compassion influences the way she attaches personal meaning to nuclear power.

Heather and Kristin discussed experiencing similar "human concerns" in their interview. In a Mothers for Nuclear blog post, Heather documents their visit to Fukushima in 2018. In it, she describes the emotions of the experience—"fear, disbelief, empathy, and sorrow"—whilst detailing the contrasts she saw in the remaining infrastructure in the physical proximity of damaged and intact buildings, juxtaposing destruction and stillness in and surrounding the affected region [473]. In the interview, Kristin elaborated on their visit:

> We drove through an area that hadn't been, you know that's still kind of off limits and it was just like, there was a car dealership with all the glass and you could see the showroom front and just completely shattered and just glass all over the ground and metal twisted and buildings just crumpled like a great big hand came out and just smooshed it up. And so the power of the natural disaster that struck that area . . . when I think of Fukushima, and this is someone who should know better but when that word is said, I think nuclear disaster, I don't think earthquake and tsunami and that's the tragedy of the whole thing to us.

The force of the destruction resided at the forefront of their recollections of their visit and illustrated the magnitude of the disaster, However, Kristin emphasised that the impacts of the earthquake and tsunami are relegated to a position of remembrance beneath that of the nuclear accident. This way of thinking, she implies, is prevalent throughout society and produces a definition of nuclear power that is unrepresentative of the wider circumstances, and this skewed narrative facilitates the drawing of contrasting conclusions from Fukushima Daiichi.

In broadly categorising the conclusions made by the interviewees, the arguments presented within can be roughly encapsulated as two diverging points of view: 'a nuclear accident happened, but ...', and 'a nuclear accident happened, and ...'. The interviewees firstly acknowledge the pain and damage of the disaster, but their attitudes then branch out according to their framing of the event, the former and latter remarks bringing into focus the respective strengthening and weakening that stems from the inherent duality of a nuclear accident. A visualisation of this finding can be found in Figure 3.3. Whilst those in the 'but' category tended to reason that the affective severities of the natural disasters contrasted to the nuclear accident, the interviewees who placed themselves in the 'and' group used the accident as justification against the continuation of nuclear power by enlarging the nuclear issue in expanding upon the sensitivities of the disaster.

One example of this division appeared in Wade's thoughts on the topic of the Fukushima Daiichi accident. He noted that the earthquake and tsunami caused "enormous loss of life but because society understands [natural disasters] because it's happened before, the social contract[6] is not broken ... it doesn't cause society to disintegrate." It was clear to Wade that the frequency of catastrophic events played a role in how well-equipped the public became with emergency procedures and their general preparedness as part of the "social contract". Given the inter-

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[6] Wade's discussion of the "social contract" was likely in reference to Rousseau's social contract theory, which stipulates that members belonging to a society act and think in accordance to a set of moral rules that govern life and behaviour in that society [474].

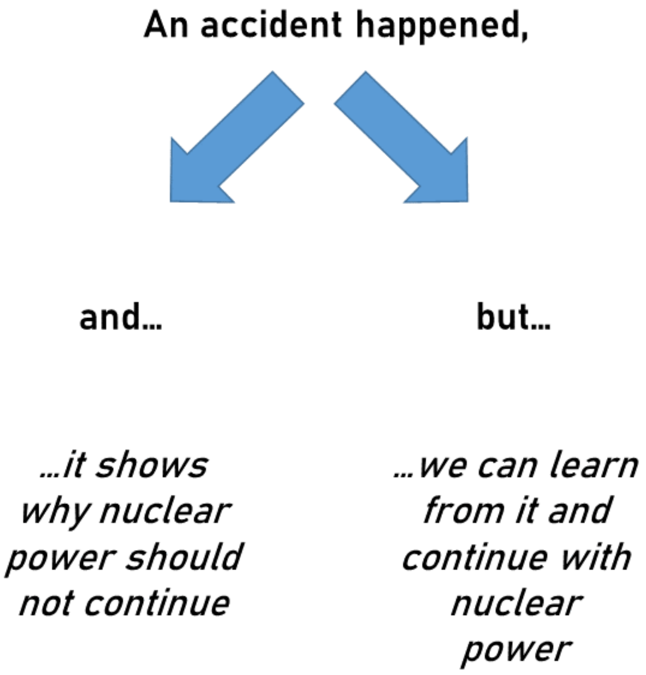

Figure 3.3: A visualisation of the two diverging points of view from the starting point of ‘a nuclear accident happened,’, into ‘and...’ and ‘but...’ statements.

connecting issues of the climate crisis, global warming, and increasingly recurrent extreme weather events, the possibility of experiencing a natural disaster in our lifetime becomes progressively more likely with time, and the understanding of the disaster is then spread throughout society down various communication streams. However, with Fukushima Daiichi, Wade discussed the breakdowns in various societal institutions and attitudes:

> But radiation and nuclear, they haven’t been told about it except that it was something that would never happen and then when it did happen, they panicked and the authorities panicked as well and the prime minister panicked . . . the belief in, not only the belief in science but the belief in the authorities collapsed and that then causes real fear and panic and social disintegration and drinking and bed wetting, divorce and all the other things like this, and loss of businesses and so on and society collapses.

For Wade, the uncertainty and undoing that accompanied Fukushima Daiichi were exhibited in the alarmed reactions of the populace and the collapse of certain societal systems. He claimed that the widespread hysteria originated from citizens possessing knowledge in which realistic expectations were absent ("[it] would never happen"), resulting in "social disintegration". It can be surmised that the meticulously-controlled operation of a nuclear power plant with its increasingly advanced safety measures could indicate that it would be less likely for a nuclear accident to occur in the coming decades. As a consequence, many members of the global population, and especially future generations, might never experience the real-time occurrence of a nuclear accident. Upon comparing this to the more frequently experienced and unyielding natural disaster with which there is greater familiarity, knowledge of nuclear processes and nuclear disaster management is less ubiquitous amongst societies globally, especially as citizens do not typically encounter the physicality of a nuclear power plant on a regular basis. Hence, the social contract with nuclear power is limited in terms of societal knowledge and actions, and Wade's 'but' statement, which ultimately centred on the spread of knowledge in preparation for the futures of nuclear power, provided insight into the lack of informational symbiosis between the public and the nuclear energy sector.

This 'but' attitude is extended in Interviewee 7's perception of Japan's improvement efforts due to the accident. Whereas Wade placed emphasis upon knowledge gaps after Fukushima Daiichi, Interviewee 7 instead focussed on new understandings gained from these knowledge gaps:

> If they're going to reopen or run, continue to run nuclear stations in Japan then you'd want to be sure that they'd eliminated the risk of something like that happening again ... I would assume Japan is a modern country that has a good regulator and that if the power stations are open again then that means that the regulator's happy that they're operating safely and they've learned the lessons from what happened at Fukushima.

For Interviewee 7, whose profession affords him acute familiarity with nuclear regulations and radiation safety, the corrective nature of the nuclear industry in Japan was understood to have had an influence on the degree to which lessons were learned from the accident. In practice, this is particularly permitted by the life cycle of nuclear power plants which undergo invariable evolution: aged plants are decommissioned, and newer plants with improved implementations are constructed, able to bear the impressions made by Fukushima Daiichi. From a wider perspective, Interviewee 7's perception of a country's status as an indicator of its ability to handle delicate technologies revealed how, in the case of nuclear power plants, modernity can be correlated with organisational and technological advancement. The scale of modernity would then control the extent at which regulators reinforce the validity of the newer plant improvements, and Japan, whose political and economic power is reflected in its "good" regulatory body, was ultimately regarded as reliable by Interviewee 7 after the Fukushima Daiichi disaster. This line of thought implies alternative discourse around attitudes towards potential nuclear power accidents in countries assumed to be less developed, the rationale behind which is more challenging to uncover from the interview alone.

After the accident, the "Fukushima" label produced evocative associations as a result of the way people derived their own meanings from the accident, exemplified by Kristin stating that in California, "Fukushima's like a hate word". She illustrated how this strong affective attachment then became embedded in societal relationships:

> What about the people that were displaced from that area? Now they're seen as dirty, they can't go back to their homes and that has real impacts on the people and it's unnecessary. So our societal fear of nuclear has this toll.

The classification of displaced "Fukushima" citizens as 'dirty' highlights how adverse material associations become imposed on particular groups of people, who then face social discrimination. Kristin mentioned a collective "societal fear"—a major emotional shift in nuclear culture, the impact of which was argued by Heather to have been the more dominant factor in policy changes: "it's not the technology, it's the fear and how we reacted to it and how we've made policy". Moreover, the recurrence of fear can drive many policy revisions. For example, the reprisal of many of the fears from the Hiroshima and Nagasaki bombings in the reactions to the Chernobyl accident is comparable to the renewal of Chernobyl fears as a result of the Fukushima Daiichi accident 25 years later [475]. The uncertainties are heightened by not only the intangible nature of radiation, but also the unique circumstances behind each nuclear catastrophe in aspects such as plant location, reactor technology, organisational culture, and changes in the society itself and the way these fears are understood. In support of Heather's comment, Kristin added: "it does matter what we think and how we act about nuclear. It's more than just an opinion because our opinions are projected on people and then they get into policy ... and world opinion". Thinking and acting after a nuclear accident becomes part of the wider implications of such an event, and with the subsequent scrutinisation of nuclear energy taking centre stage in global discussions and worldwide media reports, Kristin stressed the importance of communication and action in opinion-led policymaking. In addition to this, Heather remarked on the framing of discussions around nuclear power:

> We have to be super careful of how we talk about it because as a nuclear supporter it's easy to think like, oh no-one was killed at the plant and nothing like really happened that was bad and like some people say that but it's like we definitely don't want to minimise those impacts.

Being involved in nuclear power advocacy, Heather experientially observed that there was generally a propensity for some nuclear supporters to be more indifferent towards the social costs of the accident that were not immediately concerned with death or subjective 'badness', causing the severity of the surfaced issues to be lessened. Her awareness of the detrimental ways of framing nuclear power was also possessed by Interviewee 6, who shared a similar view in cautiousness when discussing and thinking about nuclear power after the accident:

> I think it was ... obviously a terrible kind of tragic event that was first and foremost an issue around the environment and what happened there. And I think it's important that we look to instances like that and take learnings from them. But it's also really important that we don't make assumptions that-, a very broad brush on the industry.

Although Interviewee 6's statement differed slightly from Heather's as no particular groups or actors were mentioned to be doing the assuming, they both touched on the shifts in conversations surrounding nuclear power after Fukushima Daiichi, and

Interviewee 6 specifically took note of the generalisations made upon the industry whilst also discussing the 'lessons learnt', just as Interviewee 7 had also mentioned. For Kristin, Heather, and Interviewee 6, their 'but' statements revolved around the way the Fukushima Daiichi accident was socially and culturally memorialised. In recognising that emotional reactions could play, and have played, a large part in how nuclear power is portrayed and thought of post-accident, these interviewees' 'but' statements conclude by urging caution to be taken in our conversations around nuclear disasters.

On the other hand, the interviewees who adopted an 'and' attitude drew conclusions that extended the disastrous nature of the accident. For example, Interviewee 7 reasoned that the accident incurred monumental financial impacts, stating that "it's catastrophically expensive to clean it up". Other interviewees went further into the contextual meanings of the accident, and argued for the discontinuation of nuclear power through exploring how nuclear power endangers societies. Interviewee 8 believed that "Fukushima was another explanation for us of the dangers of nuclear power", adding that:

> Chernobyl could be, you know as the drama series has shown, can be put as the accident waiting to happen because of the Soviet Communist system really and the problems with it . . . the accident in Fukushima happened largely 'cause of a natural disaster but there were warning signs and so on and you know if they'd put the sea walls that bit higher and so on, you know which had been sort of told them beforehand about was a possibility then it wouldn't have happened.

Interviewee 8's mention of "warning signs" may have referred to the nineteenth century 'Tsunami Stones' located at various points along Japan's coastline that caution local residents against building houses too low on the ground [476]. Present here is the argument that by not heeding the warnings of past generations or traditional knowledge, the likelihood of the occurrence of nuclear power disasters are escalated. With reference to the HBO series Chernobyl, which first aired in 2019 as a dramatised depiction of the Chernobyl accident and its aftermath, Interviewee 8 parallelised the situational factors that led to the Chernobyl and Fukushima Daiichi accidents through integrating their historical and environmental contexts. The reasoning that Interviewee 8 extracted from the Chernobyl series not only indicated how modern media can describe and control the narrative elements of a nuclear accident, it also evinced how it can reinforce and validate existing beliefs surrounding nuclear technologies. Interestingly, Interviewee 8 did not directly mention nuclear technologies in his explanation; rather, he ascribed the main causes of the accidents to a political ideological system and a natural disaster, and instead identified nuclear power in the "warning signs" for accidents "waiting to happen". This expectation of unavoidable risk is a reminder to Interviewee 8 that as much as the future is in the present, it is also in the past; to him, prior nuclear incidents act as forewarnings of future adverse outcomes of nuclear technologies. Similarly, Pete's perspective of nuclear accidents assigned an aspect of inevitability to nuclear accidents:

> For them to have a civil nuclear accident of the scale that they had is devastating and surely it sent a huge message out to everybody that these accidents do happen. They happen for unforeseen circumstances, the same as Chernobyl did and the same as indeed our own nuclear accident in 1957 at Windscale.

Particularly for Pete, the uncertainties in nuclear technology and its outcomes were embodied in the "unforeseen circumstances" responsible for previous nuclear accidents. It is interesting to note here that the idea that disasters are unpredictable and could happen at any moment contrasts markedly with Interviewee 8's comment on the inevitability of disasters due to not listening to warnings. In the references to earlier accidents, Pete highlighted the powerlessness of intention and preventative measures against an inability to wholly prepare for deleterious futures of nuclear technologies. For both Pete and Interviewee 8, their 'and' statements centred around the way nuclear accidents can remain and repeat throughout history and the future, placing emphasis on both clarity and uncertainty in our adoption of nuclear power. Their views emphasised how they regarded the Fukushima Daiichi accident as just one occurrence in the series of nuclear disasters yet to come, demonstrating how we are not impervious to nuclear accidents despite employing increasingly advanced technologies.

As we have learnt from the interviewees, the impacts of the Fukushima Daiichi accident have permeated far beyond the confines of political, geographical and cultural borders and throughout global societies, creating new understandings of nuclear power within its historical contexts. From Fukushima Daiichi in particular, the interviewees were able to construct their own interpretations of the accident, contrasting and expanding the devastation in their arguments for and against the continuation of nuclear power. The future of Fukushima Daiichi is carefully managed in the restorative and remediative work that has been primarily carried out by TEPCO and the Japanese government alongside citizen efforts, and the accident has set new precedents in the nuclear industry, for instance, accelerating developments for alternative fuel technologies, and setting new standards for risk management. The faults and mismanagements of the Japanese government, and TEPCO were scrutinised, ultimately compensating evacuees after a court held them to account for their lack of preventative action towards the power plant [477].

In Fukushima and the surrounding regions, decontamination and cleanup efforts are currently ongoing; plant decommissioning is estimated to be completed by 2050 [478]. Vast quantities of water became contaminated from cooling down the melted fuel debris, as well as from the groundwater and rainwater making contact with radioactive materials onsite [479]. To treat it, various filtering and radionuclide removal facilities have been used, resulting in 1.3 million tonnes of treated water being kept in storage tanks so far. The Japanese authorities have planned for its gradual release into the ocean, intending for the treated water to be diluted over time to decrease the concentration of the difficult-to-remove tritium [480]. However, announcements for these plans were met with widespread condemnation; the impacts that the associations that come with radiation and contamination would have on livelihoods and attitudes presented a sensitive issue for the authorities. The delicate aftermath of a nuclear disaster therefore requires the considered navigation of sociopolitical contexts, insofar as a Japanese MP drinking treated water before journalists during a press conference [481], amongst other dealings of the wastewater crisis involving the authorities [482]. The difficulties of ensuring the sustainable future of treated water provides an excellent example of the intricate balancing acts that are involved with addressing futures after a nuclear accident like Fukushima Daiichi.

It has been clear that the materialities of nuclear accidents have become a stark reminder of our intimate connections with nuclear materials and the power of creating associations with meanings that encompass the wider picture of the accident. As such, it has necessitated listening and learning from previous nuclear disasters; much like Chernobyl, Fukushima Daiichi has become another way for people to establish the significance of large-scale nuclear events that may occur in the future. As we have seen in this section, the interviewees, who approached the topic of the Fukushima Daiichi accident and its aftermath using both ‘and’ and ‘but’ lines of enquiry, have addressed many of the complications arising from the accident and their personal connections to the disaster and its meanings. Their experiences and outlook have evidently magnified the futures of nuclear power and our relationships with its materialities for generations to come; this continues in the subsequent themes in this chapter, and allows for more insight into the complexities of nuclear futures.

3.5.3 Attitudes and attachments

Attitudes and relationships affect the way we make meanings and establish understandings of our societies, environments, and circumstances. Within the discourse surrounding nuclear power, the nuclear industry embeds itself as a key actor by virtue of its prominent role in the development of nuclear energy. Its involvement and governance in fuel manufacturing [483], reactor management [484], and plant decommissioning [485] gives rise to emergent social entanglements, and generates new meanings and understandings of industrial relationships. Hence, it is clear that the nuclear industry plays a significant role in the social narrative of nuclear power.

In its early stages, the nuclear industry was indifferent towards fostering trust in the general public; for instance, perceiving the general public to possess a limited understanding of the technicalities of nuclear power and excluding them from decision-making [486]. However, with public opinion increasingly having an effect on governance and policy, industry relations with stakeholders needed to evolve in an attempt to reconcile nuclear technology with society, such as providing more engagement and outreach opportunities with the public. Interviewee 5 discussed the public response to the UKAEA's outreach activities, observing that in the outreach sessions, they are "talking to people who are relatively well versed about fusion. If they're not, they're pretty positive about it. They're coming in with an open mind". Janet substantiated the claim that UKAEA's outreach focusses on people who are open minded; when asked about her views towards nuclear fusion, she replied: "I think I need more information to be honest with you. I'm open to find out about it, I'm open to hearing what the benefits are, hearing what the negatives are and to see what the balance is".

For the majority of people attending the outreach sessions on nuclear fusion technologies, Interviewee 5 noticed that they were scientifically literate, and therefore the outreach and communications team would "rarely get particular levels of hostility or scepticism … and that's a problem for [the team]". In being unable to reach target groups, such as those with similar views to Janet's and Pete's, early interaction is restricted. As a result, Interviewee 5 would only be able to depend on the UKAEA's efforts to change the affective associations for nuclear fusion only, such as attempting the change the cultural lexicon to distinguish between physical processes, as Interviewee 5 explains:

> We're very conscious that we don't want people to think it's just another type of nuclear fission because it isn't and therefore to the wider public, we will and are already starting to not use 'nuclear fusion' and use 'fusion energy' as a phrase.

In attempting to alter perceptions of fusion technologies through changing its label, Interviewee 5 highlighted the significance of forming early attachments and connotations with nuclear energy, especially for shaping future perspectives. Interviewee 8 noted the absence of primary educational initiatives for nuclear power and the impact of distance on broadcasting disasters, remarking that:

> [He noticed] particularly in the younger generation, sort of your age really a great lack of knowledge about nuclear power you know. When I start talking to university students about it it's quite clear they've not really engaged in it really, and some may have had a little look at it when Fukushima happened but again with Fukushima being over in Japan, a long way away from us, again and not getting a lot of coverage in this country.

On this, Interviewee 6 suggested that education around nuclear power "should . . . potentially [be] part of the curriculum", adding that "we really need to be starting in schools and looking at how we educate young people on how we can tackle climate change". However, Pete questioned the notion of educational pursuits altogether, arguing: "well there isn't education is there, there's indoctrination". Here, Pete conveyed the common emergence of the monodirectional transfer of knowledge in the nuclear industry, and the perceived restrictions in the beliefs in the technological applications. Some interviewees gave further insights into how the nuclear industry has tried to construct understanding, such as Janet, who described her town's difficulties with EDF's information displays:

> There would be big areas on display, masses of information to take in. And so they would go round to the local villages. It would be in Leiston for round about, longer than the other villages. It'd be, oh I don't know something like three to five days here perhaps but some of the villages it'd be like just an afternoon and if you happened to work you would miss that opportunity, you would have to find an alternative to looking at it.

Upon mentioning the barriers that working people face in accessing certain avenues of information, Janet also highlighted the inconsistencies between local knowledge and EDF's information, claiming that in the consultations, "the maps are awful". However, Janet recognised the significance of the relationship between nuclear power organisations and the local community, and mentioned attending their local stakeholder meetings:

> We live in that Evacuation Zone and . . . we're considered as a local to Sizewell B and when they have meetings with the local residents I go because it's good to keep that rapport and relationship going. They've been very fair with the thing, the demands that have been made by the local group.

In her interview, Janet described herself and other local residents as being very highly involved with the Sizewell reactors through engagement events and communication:

> When Sizewell B itself was being constructed we were frequently invited to go and look at the stage of construction being a local resident and we used to take that opportunity, one because it was an amazing construction regardless of your views on nuclear power. The construction was quite extraordinary and they did do certain things like the light pollution at the time, at the early stages of construction was absolutely hideous but we complained and the lights were turned down. So there were a certain amount of things, co-operation as a neighbourly thing was happening.

Despite the neighbourly co-operation, community action from local residents revealed the disconnect between their lived experiences and the plans for the Sizewell reactors. In the implementation of large-scale changes in an inhabited area, information imbalances arise as a result of the exclusion of local knowledge. With Sizewell B, this provoked perceptions of inadequacy and distrust amongst the local residents; as Janet stated,"it feels like it's been years that we've been fighting this and they say, oh we didn't think of that. So that doesn't make us feel very confident". In particular, Janet described the allure of the interactions during engagement with Sizewell C:

> When they started to talk to us last week about the bridge over the SSSI, what they were going to do there and it's such a sort of sweet-talking seduction. I almost found myself saying, yeah bring it on . . . and I thought, Janet, you've just been sucked in to this whole speech. 'Cause when you listen to them and once they get on their roll, oh yeah they've done this and they've done that and they've done that and they've thought about that and etcetera and it'll be fine. All the snakes and the newts and the bats and the dragonflies and the butterflies that are rare Red Book listed creatures, they're all going to be fine. Some of them might suffer of course and oh dear the birds might do this and-, and you begin to think, well yeah it doesn't sound too bad. But then when you stop and think again you think, oh for goodness sake you know. Have you thought about this and this and this?

Here, Janet referred to creatures listed in the "Red Book" – the International

Union for Conservation of Nature (IUCN) Red List of Threatened Species [487, 488]. As Janet indicated in her interview, the strategy that the Sizewell C stakeholder engagement team uses to present various scenarios – albeit effective in persuading communities – minimises, and in some cases, removes the affective implications of substantial changes. Through Janet recounting some of the messaging in a matter-of-fact manner, for example “some of [the rare creatures] might suffer of course”, her perception of Sizewell C’s engagement methods demonstrated how sentiments and sensitivities can become divorced from the harrowing realities of significant change in energy narratives, to the extent that Janet briefly put aside her values and principles during this particular interaction with the stakeholder engagement team.

Later in our interview, Janet detailed how local ideas and knowledge were co-opted into EDF’s dialogue:

> People criticise this culvert for the animals. They said it was too long and too dark and then now it’s become EDF’s talk that it’s too long and too dark. Because it’s too long and too dark we had decided and the bridge that we were suggesting was too big. Now it’s going to be a single carriageway so look at how good we are at listening to your ideas and thinking about the animals that live there.

Evidently, Janet perceived EDF’s attempts at adopting the concerns of local residents as insincere, and from her position as an ardent supporter of environmental and ecological protections, EDF’s attitudes towards the safeguarding of animals would appear to be more a façade. Moreover, she illustrated how raising local concerns and challenging industry plans and decisions can be particularly arduous, and imagined how impressions of Leiston and its residents have aided in establishing EDF’s own attitudes:

> And not everybody’s got the time, the energy, the patience, the will, the motivation to do that. So I feel we’re being walked on. I feel we’re a doormat. Oh the people in East Suffolk, particularly in Leiston are very–, they’re not known for their subversiveness, they’re not known for their resistance, we’ll build it there.

On the topic of face-to-face interactions with EDF, Janet reflected on the meetings that she attended, and the attitudes of the employees who ran the meetings. Some of the EDF employees stood out to her in particular:

> There were two EDF chaps and the one, the main one who was running it, he was very polite. He was not condescending but there was towards the end a touch of condescension in his voice ... he kept saying–, this is what irritated me towards the end. It's your meeting, it's your meeting. You can take it where you like. And I kept thinking, mm I don't know if I like the sound of that.

Representatives of a company are to some extent its corporal embodiments, and are therefore important for fostering relationships with the general public. When such a relationship becomes strained due to representatives' ill temperaments, the resulting negative perceptions of the company can lead to the erosion of communication, as Janet emphatically detailed in her interview:

> I've been to meetings when the person running it has been so rude. I won't go to him in particular, I won't name him but when one particular member who frequently runs the meetings is doing it I say, is so and so and so and so going to be there? And I won't go 'cause he is so rude. He gets angry and so people ask him this question and that question because of their concerns about that and this and he–, after a bit he then starts to get irritated by it and you can see the anger emerging in him. And emails from someone in TASC has had from him are down–, I mean it's there in black and white, downright rude.

Her conditional attendance of the meetings exemplifies how relational affective disintegration can emerge from negative perceptions of the nuclear industry—in this case, the "rude" EDF employee caused an attitude shift for Janet, who consequently regarded the meetings in a cautious manner. Furthermore, her metaphorical use of "black and white" highlights the absolute clarity of her impression of the representative and the extremity of his behaviour. In her interview, Janet described another EDF representative who had a similar attitude to the "rude" employee:

> The other bloke who was there, I was waiting for him to erupt. He seemed to be a person controlling his temper all the time. I could be wrong on that but that's what it felt like. It felt like when he was asked to speak which wasn't that often, it had that edge if you know what I mean. It had that edge. I was thinking, well actually you're getting paid to speak to us. We are all doing this in our own time. It's our money, it's jumble sales when we were allowed to do jumble sales, you know it's begging letters now because we can't have fundraising oppor–, there's no fundraising opportunities because of COVID. So I was sitting here thinking, don't get irritated with us matey because you're

> getting paid to sit there and listen and we certainly aren't. And that's the same for all of these different opportunities to meet with EDF. They're getting paid to be there at six o'clock at night.

As shown here, Janet's instinctual perceptions as a result of this particular affective characterisation of nuclear power played a part in developing her attitudes towards the nuclear industry. She illuminated the financial and emotional barriers to campaigning—another indication of the personal taxation of being an anti-nuclear campaigner, which she also made mention of earlier in our interview. The emphasis that Janet placed on profession versus passion highlights the power of affective attachments in shaping narratives; it is suggested here that passion presents the production of emotional ties, and profession more of a demarcation in terms of personal attachments. Janet's use of language here is also fairly revealing; by referring to the EDF representative as "matey", she conveyed her irritation at his volcanic behaviour in the context of the distinction between personal dedication and an employment obligation. Janet contrasted the unpleasant attitudes of the Sizewell C representatives to their Sizewell B counterparts:

> I'm not complaining about the staff that used to run Sizewell B. I don't know who the new person is now because the person who used to run it has moved on. They were polite but when you got the Sizewell C people then it always seemed to be one, ignorant and two, rude and that is–, that doesn't make you feel reassured. Why are you being rude at us? Why are you not knowing when we ask about this particular place? This is going to be destroyed. Why haven't you found that out? Surely you would have guessed that questions were going to be asked about the woods, the beach, the habitats, the roads and so on.

Through her frustrations at the impolite and poorly-informed Sizewell C representatives, Janet showed in her account that attitudes are often transmissible. The absence of 'reassurance' hinders the communicative aspect of the stakeholder sessions, leading Janet to ultimately realise that "as a protester you do have to relate and listen to the developer because if you don't relate and listen to them, then what you say can be ignored". Furthermore, she stated that "we're not given the answers. So I suppose that I've been brainwashed, seduced, sucked in" in stakeholder communication sessions with EDF. This is particularly exhibitive of whom the active and passive actors are within the power asymmetries in nuclear energy engagement, and speaks to the information dissonance that arises as a result of such asymmetries. Interestingly, Janet revealed an alternative pathway for information:

> I suppose what reassures me to be brutally frank is that my son-in-law is one of the people who works in the control room. So knowing somebody that works in the control room I think helps. I trust him, I trust him implicitly with his views on safety. And he's got two little girls. I trust him so I think that's where some of the trust–, I've known him now, oh I don't know how long they've been together, at least ten years and so that has helped how I feel about it. So it's not the Local Authorities, it's not EDF, it's not national government, none of those people that you would expect to do the reassuring and the constructiveness. It's who you know.

Through this close, familial connection, Janet's concerns were slightly more assuaged, especially given that her son-in-law oversaw the complex operations of the reactor in the control room. Janet's trust in her son-in-law and her distrust of authoritative voices signifies how relationships and attitudes have become intimately entangled, and how confidence in nuclear technologies has become inseparable from personal associations. Interviewee 7 corroborated this:

> A lot of the British public is not particularly up to speed on nuclear issues but of course the communities that are most active in my network are communities where a lot of people are employed in the nuclear industry so they kind of do get it, you know and they are, they have a different view of nuclear than maybe the general public does because they know a lot of people who work in the nuclear industry or they work in the nuclear industry themselves.

Other interviewees also shared their views and experiences regarding the way their social connections had shaped their attitudes. For example, Heather described how her initial apprehension towards nuclear power intensified: "I was nervous about it and my family was nervous and they made me more nervous". Kristin expressed similar early attitudes: "I just had a negative perception about nuclear and I thought I was going to hate it and I didn't want to know anything about it". As both Heather and Kristin transitioned into pro-nuclear campaigners, their experiences bring to question the extent to which initial perceptions matter in the formation and evolution of attitudes.

In our interview, Kristin recounted her participation in a national radio talk show. After being invited for a discussion on the topic of nuclear energy, she soon found out that the show organisers had somewhat belatedly invited another guest—an anti-nuclear campaigner. Kristin explained that she "just wasn't prepared for a debate when we got on the show because I was thinking we were going to have a conversation", implying the combative approach of the anti-nuclear campaigner. Furthermore, she noted:

> It was just like impossible to actually have a conversation about things we both cared about. Because I could tell we both cared about a lot of the same things and if we were to actually have a conversation about what are the best ways to address some of these issues, I bet we would agree on a lot of it. But it was just so difficult because it wasn't that she wanted an answer to any of those things, she just wanted to get in a bunch of anti-nuclear soundbites. And also it was a little bit dirty too in a way and I hate saying that because I just still feel weird about it but I said something in support of nuclear and then for her soundbite she said, well I agree with Kristin we don't need nuclear, which is obviously not what I'd said but she was just try–, like that was just another soundbite she was trying to get in. And so it's like, it's representative of a lot of the experience I've had in that the other party doesn't actually want to have a conversation about the issues. They just want to get in their soundbites and move on".

As a consequence, Kristin found it "frustrating" to "debate" the anti-nuclear campaigner and her "disparate" statements. Additionally, Heather observed that "you know it sounds like kind of, like oh my gosh they're being dirty and sketchy but I think it's really important to talk about that because we were just so shocked that that happened and that the host didn't call it out". Here, Heather further reflected upon the anti-nuclear campaigner's antagonistic surface-level attitude–"dirty and sketchy"; through her use of irony, saying "oh my gosh" in mock surprise, Heather indicated there were layers to the anti-nuclear campaigner's attitude due to their own agendas and motivations when broadcasting ideas on a national radio show. Both Kristin and Heather remarked on the regular occurrence of this "phenomenon" and how it often results in opposing attitudes restricting the space within which balanced conversations can be held. Contemplating on her interactions on the radio show, Kristin concluded that "it does matter what we think and how we act about nuclear. It's more than just an opinion because our opinions are projected on people and then they get into policy … and world opinion".

On EDF's relationship and communication with anti-nuclear activists, Interviewee 6 remarked that it was "very much a two-way street", and mentioned that "we routinely kind of deal with you know anti-nuclear you know opposition to the project. It tends to be a very minority of people but they can be quite vocal". Interviewee 6's use of the term "deal", which possesses a slightly negative connotation, implies an encounter with a challenging or difficult actor, and the 'vocal minority' trope, which is usually used as a synonym for troublemakers, indicates a dismissive attitude. In comparison, Pete found his interactions with EDF to be belittling; he stated: "I don't like the way they sort of minimise the problems that I've been working on for a long time". Moreover, the general attitudes present in the communication between EDF and members of TASC tended to contain sentiments along the lines of frustration and dissatisfaction, as illustrated by Pete:

> I wish they were a little bit more candid about the uncertainties that exist in the nuclear issue. So I suppose they're a bit fractious you could say and the relationships are a bit fractious and now we have the situation where the planning inspector and EDF want us to complete a very long document called Statement of Common Ground. So EDF state their position on certain issues and we have to state our position on certain issues. Well I'm sorry but there is no common ground between us. We don't want the thing built.

Pete elaborated on his vehement rejection of nuclear power and the impossibility of reconciling his views with those of EDF in documentation:

> And it's analogous to me to being asked you know, how do you want the deckchairs on the Titanic arranged. Well we don't want to get on the Titanic in the first place thank you very much. We don't want to enter into those negotiations which legitimise the development.

Here, Pete identified parallels between nuclear power and the Titanic—the 'unsinkable ship' [489]—and drew upon its general use as a metaphor for a catastrophic failure, and its symbolism for unexpected disasters and eventual tragedy in technological implementations. This analogy was bolstered by Pete's use of the personal pronoun "we"; not only is it a representation of a collective attitude within the community, it also echoes the cumulative social toll from the Titanic disaster and lends power to contextualising the scale of the tragedy. As such, prevention of a nuclear disaster of this magnitude lay in the unwillingness to partake in negotiations, as "legitimising the development" equated to acceptance.

Holding a different attitude to many of the other interviewees, Interviewee 7 expressed more neutral views towards nuclear power, stating "I'm generally personally quite agnostic about nuclear", conveying distance in his attachments towards nuclear power. Nevertheless, Interviewee 7 believed that for seemingly inexorable technologies such as nuclear power, an element of greater consideration is required, arguing that "proposals for new nuclear stations of all sorts need to have recognition of the need to engage with and win over the community rather than impose things on the community". This recommendation, on the particular inclusion of communities in nuclear power developments, places emphasis on applying a more transparent approach to stakeholder engagement. Interviewee 7 suggested that where the community becomes more involved, the process becomes demystified, potentially impacting attitudes towards nuclear power.

Interviewee 7 provided commentary on the opposition of nuclear power, and noted that the visibility of attitudes determines the level of perceived consent:

> There's totally fair questions about the cost of Hinkley C and so on but there's not been any sort of big public outcry, so again going back to your point about community consent, I mean in general the British community is sort of consenting to it because there's not much sign of very large-scale opposition. Something like fracking was very different you know. There was a lot of people on the ground protesting and there was a wider lot of people engaged against it. Hinkley Point C nuclear station, there's not been those sort of protests or anything really around it.

Expanding upon this point, Interviewee 7 reflected upon the observed attitudes of pro- and anti-nuclear groups:

> Some on the anti side would say that the nuclear industry is making claims about climate change just to justify what it's doing and some on the nuclear side would say that the NGOs are being disingenuous in saying we can achieve

> this without nuclear and so on.

Within these attitudes, Interviewee 7 regarded various elements of insincerity to define the relationship between pro- and anti-nuclear actors. Evidently, the emotive components of socio-technical narratives become significant when considering opposing attitudes. Interviewee 8 concurred, and remarked that “it’s an issue that creates passionate views both sides of the debate”. In recognition of the sensitivities of the technology, Interviewee 8 explained the origin of the naming of the NFLA:

> Our strange name comes from the fact we didn’t want to call ourselves anti-nuclear because that could create very negative connotations for us. Nuclear free is a more positive aspiration that we’re looking to see a world that’s free of nuclear power and weapons eventually.

By incorporating affective associations in a collective identity, Interviewee 8 acknowledged the ways in which attitudes can impact one’s stance on nuclear power, and highlighted an attitudinal demarcation:

> It’s an area where there’s no chance to be neutral. You’re for it or against it. It’s difficult nuclear politics, it’s often dirty, it’s often unpleasant, never enjoyable. I don’t enjoy nuclear politics, I’m quite frank, I really find the antagonism of it quite difficult and frustrating. But that’s because the people involved are coming from two very different backgrounds.

These comments bear resemblance to Kristin’s views on engaging with anti-nuclear campaigners, where she felt that her debate with the anti-nuclear campaigner was “frustrating”, as well as “dirty” in the sense that the arguments around nuclear power are like dirty fights that encroach on personal boundaries. Interviewee 8 expressed his view on how antagonistic attitudes have become an established part of the relationships entangled within nuclear power, stating that “nuclear politics will always be adversarial, it’ll always be challenging and robust and very rarely come up with consensus”. For Interviewee 8, this emerged in relationships with governmental groups:

> It tends to be very frustrating with the UK government I have to say. There’s usually what we call a dialogue of the deaf going on really. That’s how I would describe a lot of nuclear policy stakeholder consultation really as well you know . . . we get stock answers really you know, when we speak to civil servants.

In the absence of receptive listening and authentic dialogue, the affective attachments in these fragmented relationships eventually become embodied in the attitudes; Interviewee 8 felt "deeply frustrated that you feel that you're not listened to . . . you're patronised I feel, a lot of the time", and indicated this metaphorically: "very quickly you feel your head gets sore from hitting walls all the time". Interviewee 8's attitudes largely feature the relational effects from the power imbalances between those who control and those who do not, and discussed this in our interview:

> It's not a very uplifting job in a way, in a sense to challenge it really 'cause you are dealing with very big powerful institutions really who are fairly intransigent when it comes to listening to you on these things really. And so you don't get a fair hearing a lot of the time.

Alongside existing biases, Interviewee 8 also mentioned how beliefs and perspectives can shape actions and attitudes:

> You tend to find the further away you are from the reactor the more opposition you'll get to it really . . . you're finding an awful lot of very well organised opposition to it you know because they are confident middle class communities generally speaking.

By demonstrating how personal identities and positionalities can determine attitudes and actions, Interviewee 8 corroborated Janet's comment on feeling like a "doormat"—indeed, for those who are considered local to a nuclear reactor, the corresponding power imbalance becomes a lived experience, and therefore efforts required to campaign against any industry plans would require more time and resources from the community. Alongside this, Interviewee 8 also spoke on the impact of social behaviours on attitudes, noting that "it's not an issue that many people are interested in unless it impacts on them", and that "motivations for people can be very different". Wade shared similar comments on social behaviour, focussing on a sense of belonging and community: "people have a need to identify with other people and it doesn't matter actually so much to them–, it doesn't matter what the cause is". Through perceiving these affective social attachments in current attitudes towards nuclear power, Wade highlighted the societal expansion and commonalities in shared attitudes, and implied an emotive aspect to such attitudes. Yet when Wade objected to my labelling him as a pro-nuclear campaigner, he stated that “there’s no sentiment associated with it. It’s just as a judgement, as a science”. Here, he expressed denial that supporting nuclear power involved more complex and multidimensional attitudes, and seemed to dismiss the emotive facets of nuclear identity, arguing its comparison to a “science”. His comment on the element of identity may stem from how he views the validity of his position—rather than ’merely’ affective or emotional, it is one that is grounded in science and rationality and therefore has more weight attached to it, compared to ’irrational’ emotional beings: the anti-nuclear campaigners.

In the past century, secrecy surrounding nuclear technologies has become a defining aspect of its characterisation, which in turn has prompted shifts in attitudes towards nuclear power that lean towards distrust [490]. The history of nuclear power contains many examples of this; for instance, during World War II and the Cold War, nuclear espionage fuelled the development of atomic weapons in rival countries. Notable spies such as Klaus Fuchs and David Greenglass passed confidential information and documentation to the Soviet Union in the mid-twentieth century [491], which resulted in “hysterical” reactions to the reported spy threats [492]. During this period in the UK, certain information was prohibited from disclosure and illicit dissemination, a move initially directed by the Atomic Energy Act 1946 [493]. Interviewee 5 explained how public attitudes were shaped by the continuing control and obscuring of information with respect to the contextual history of nuclear power:

> Back in the ‘70s, ‘80s, ‘90s they almost certainly didn’t do enough and some of the tarnishing of the reputation of fission which is clearly there came from the fact that they just didn’t engage. They were a very secretive kind of organisation.

Interviewee 5, in using “organisation”, alluded to the nuclear authorities and officials controlling the nuclear power systems. Interviewee 5 then shifted the focus to the present day, and expressed that “I think it’s still viewed as a very closed community and one where you know, the problems are not shared very widely". In addition to this, Interviewee 5 stated: "I work in communications, not marketing. I am very very honest and open and I think that's the way communication should be done and we will be very open and honest . . . you've got to be as open and transparent as possible". Using the unique perspective that his career brings, Interviewee 5 distinguished between the communication and marketing professions, and heavily implied an element of disingenuity with the latter. Interviewee 6 echoed Interviewee 5's comments, stating: "we're very open and transparent as an organisation". However, Janet disagreed, stating that "there has to be something a bit more transparent and clear than what we've got". She elaborated on her comment by drawing on her experiences at engagement sessions:

> Every Sizewell stakeholder in group meetings it comes up. When we had them three times a year it would come up three times a year ... What's the emergency going–? And then you got the door closed again. The door closed, so it makes you feel more uncertain when doors are closed. If doors are opened and information's given to you and practices are held or explanations are given as to why not, in a transparent and open manner, then you calm down, you stop asking the questions. But we haven't stopped asking them.

Janet's usage of closed doors as metaphorical imagery placed emphasis on the inaccessibility of information within power dynamics, which Pete also touched on as he described how "the information is gradually being squeezed out of EDF". Addressing this information imbalance, Pete suggested that in order to effectively communicate, there is a need to "have a sensible open debate about it and not one that's conducted behind closed doors of government. It should be in the public domain. We should have it all out in the open". Interviewee 8 shared similar sentiments to Janet and Pete:

> Well we want to see the industry being much more open to the public. It's a very secretive organisation which comes out of its background 'cause of the safety and security and the defence side of what it did. We want to see public decisions being done sensibly, properly with transparency as well.

Evidently, the restrictive nature of the nuclear industry results in feelings of distrust and a lack of confidence in nuclear bodies due to the inability to reconcile personal, individual knowledge with concealed information belonging to the nuclear industry. Despite this barrier, the persistent efforts of the activists in accessing and retrieving information demonstrate the degree of their activism, and show how attitudes and actions can be inextricably tied to identity.

Many interviewees exhibited identity-driven attitudes, particularly corresponding to familial relationships. Wade mentioned having six grandchildren, and added that although he was retired, he had "a lot to work for". In a similar vein, Janet challenged the societal dependence on nuclear power, expressing that "it's the legacy for our great grandchildren and their great grandchildren and thousands of years. How can we reasonably do that for future generations?". Furthermore, she contextualised her experience in the aftermath of the Chernobyl accident by including reference to her family:

> I felt dreadful when Chernobyl happened because we were told not to peg washing out. I had a small baby then in 1985. We were told not to peg washing out, we were told to keep indoors because of the rain raining down, the particles from the Chernobyl explosion. So that was very frightening.

Janet's implicit vulnerability due to caring for a "small baby" and her "dreadful" and "frightening" emotive attachments to the Chernobyl disaster become amplified due to her identity as a mother. In her response to my question around her message to future generations, Janet began apologising:

> I'm sorry. I'm sorry that I didn't do enough and I feel very emotional about that [TEARFUL]. I'm sorry. I feel really really sad about that. I've now got six grandchildren and the idea of handing over to them all this ignorance and no solutions is so irresponsible.

Here, Janet reflected upon her personal obligation to her grandchildren as a grandmother, desire to protect her grandchildren, and her perception of her insufficient actions as an anti-nuclear campaigner. Janet's responses to my question indicate clearly how the entanglements between identity and attitudes are critical for futures narratives. She later explained her emotive reaction to my question: "it's such an emotional subject and when you, you know when you start thinking of your grandchildren. It's hard". Through her reflexivity, Janet acknowledged the affective complexities of nuclear power. Heather expressed realisations and sentiments similar to Janet's, centred around reproductive futures:

> When our company decided not to relicense the plant it was suddenly like, oh my gosh, I should have been doing so much more and so it's not really like guilt but like a sense of duty and a sense of like I–, it's my job to share what I know with the rest of the earth and specifically mothers and women who are scared of nuclear because I was too.

Here, Heather related her role as a producer and bearer of knowledge to her perceived responsibility to mothers and women, particularly regarding the idea of being in the position of a nurturing role. Noticing this shared theme of responsible motherhood, I queried Kristin and Heather on the naming of their organisation, as well as their identities as mothers and pro-nuclear activists. Kristin explained the conception of Mothers for Nuclear:

> When Heather and I were doing research on the origins of the anti-nuclear movement, you know you saw mothers, women and mothers at the forefront, you know holding their babies at the podium and it's a powerful image right, and motherhood is associated with care and protection and you know future generations.

Her reference to "future generations" mirrors the motivations of both Wade and Janet, and indicates a continual transfer of responsibility. Additionally, the powerful visual and perceptive attachments that Kristin discussed here imbues their actions and intentions within Mothers for Nuclear with meaning. To this, she added a mention of the "conflation of nuclear peaceful uses with nuclear energy with nuclear weapons and the need to protect children. You know mothers are just like woven throughout that story". Similar to anti-nuclear organisations such as TASC, Heather and Kristin's community of mothers who support nuclear power have enabled kinships to grow and for ideologies and beliefs to solidify. As we have seen in this thematic cluster, the recurrent attitudes, associations and affective connections illustrated by the interviewees have evidently been essential to the creation of their narratives and interactions. For a seemingly inexorable technology such as nuclear power, the attitudes that pervade throughout current narratives and discourse can critically determine and influence decisions and perceptions, consequently directing the emotive pathways of the many futures of nuclear power.

3.5.4 Discourse and narratives

In each interview, the interviewees provided strong commentary on how narratives in the media are shaped by journalism, and the role of the media in subsequently shaping public attitudes. Journalism is fundamentally not unbiased. Reeves, Mckee and Stuckler identify print media in the UK as 'highly partisan', and describe party allegiances as aligning with the vested interests of the owner of the newspaper, referencing Rupert Murdoch's decision for *The Sun* to publicly support Tony Blair's Labour leadership in 1997 until the mid-2000s—a deviation from its long-established backing of the Conservative party—which caused a significant increase in the readers' support for Labour [494]. The political leanings of newspapers shape their attitudes toward issues such as nuclear power, and their content can subsequently influence the consumers of such media, dependent upon cultural thematic resonances, sponsor activities, and alignment with media norms and practices [495]. Correspondingly, the opinions and values of news consumers impact how they view the political orientations of the news outlets they use [496]. The public discourse and debate arising from individual understandings of media is then a "part of the process by which individuals construct meaning" [495, 497].

The rhetorical language in journalism around nuclear power can be particularly polarising, and often frictional: e.g., "the nuclear fight for sizewell" [498], "nuclear power station could destroy wildlife haven" [499]. The terms "fight" and "destroy" demonstrate violence between various actors, and paint developments in civil nuclear power as volatile, thereby imposing a certain perspective on news consumers in order to elicit personal responses and reasonings. Here, the language constructs powerful meanings of nuclear power for the public, which then influences their individual nuclear narratives through the way they extract emotions from meaning and the formulation of judgements.

Accidents become a channel through which widespread media and public analysis of nuclear power can take place. German media outlets outlined the Fukushima-Daiichi accident in critical detail and turned “every citizen into a nuclear physicist to ensure everyone understands what exactly went wrong at the power plant”, whereas in the UK, news reports on troops in Libya took precedence and the accident was less catastrophised [500]. Perko, Turcanu, and Gennen found that soon after the accident occurred in 2011, it was negatively framed in Belgian media through the “collective memory” of Chernobyl, with initially intense coverage decreasing as time passed [501]. Particularly for younger people in the Anglosphere, memories of Chernobyl are also shaped by journalism in the form of the series based on the Alexievich book [37]. I have found comparatively little research on media reporting in countries in the Global South on nuclear accidents in the Global North, possibly due to such research being undertaken in languages other than English. However, it is of interest to evaluate how accidents might have changed public opinion towards nuclear power plants such as the Embalse and Bushehr plants in Argentina and Iran, respectively.

Palfreman presents an in-depth discussion of the narrative power that journalists hold in their storytelling, and the editorial decisions that guide the psychological influences that affect the general public’s evaluation of risk, who themselves hold a limited understanding of nuclear power [502]. He also notes that in France, “the authorities have worked hard to communicate with the public rather than leaving the field to antinuclear groups”, thus denying journalists exclusive opportunities to report on specific avenues of nuclear power. Ultimately, the formulaic strategy for engagement toward “unbounded” technologies is dependent upon the ability to generate and sustain social comprehension and contextual conversation around risk assessment. To receive a certain perspective toward nuclear energy in such a direct approach by powerful institutions suggests a careful and calculated control of the narratives by which the public understands nuclear power in France.

Doyle's study on the media reproduction of governmental commitments of nuclear power in the UK found that the framing around new nuclear policies changed over time, with initial opposition developing into support and discursive elements of climate change appearing and disappearing throughout various policy changes. Doyle also noted the absence of citizen voices of the newspapers examined and xenophobic undercurrents present when discussing the importation of 'foreign energy' [497]. In Ireland, the generation of electricity from nuclear sources is prohibited and the proximity to the nuclear waste reprocessing plant in Sellafield prompts safety concerns. However, Devitt *et al.* have explored the policy inconsistencies over Ireland's electricity imports from the Wylfa nuclear power plant in Wales through assessing media activity [503]. They reported that articles opposing nuclear power in Ireland, which were focussed considerably on health and safety concerns, were significantly greater in number than pro-nuclear articles, which tended to be opinion pieces critical of anti-nuclear campaigners and the Irish government. Essential to their argument is the deprivation of conversation around Ireland's energy futures through the thematic limitations in Irish media outlets; the lack of detailed discourse on environmental matters was suggested to have implications on the public understanding of climate change. These widely ranging discursive shifts in media are emblematic of the way significant events, places, and institutions shape the public conversation of nuclear power.

In general, the interviewees spoke of differentials in journalistic media: regional and national; bias and impartiality; illumination and concealment. In particular, the sentiments expressed by the interviewees towards these portrayals frequently correlated with their alignments towards nuclear power; supporters usually felt that nuclear power was sensationalised, whereas opponents generally felt that their voices were not represented enough. This suggests a permanent chasm between certain individuals and groups, irrespective of stance, and the media. The distance is perpetuated by virtue of the societal role of journalistic media as a primary propagator of information through various media frames [504]. The required relations with information providers such as energy companies, governments, or nuclear opposition groups enforces an imbalance in many media reports on nuclear power for specific groups in following the binary ‘pro-’ and ‘anti-’ division so commonly found in nuclear discourse, fuelled by various agendas and political backings. This imbalance was experienced considerably by the anti-nuclear interviewees in the form of media resistance, with Janet expressing how “the airtime given on radio or TV is not as balanced as perhaps as it should be”, further describing it as a “concern.” Her attitude towards the limitations imposed by mainstream media on anti-nuclear beliefs were echoed by Pete, who likened attempting to publicise outputs from TASC’s research in the media to “pushing against a very closed door”, remarking that “the local paper has been far more open to our letters and our points of view”. Given that the extent of the control of national media by powerful corporations is far greater than local media and thus reflects a more restricted viewpoint, the diversification of views in regional publications reflects the value of upholding local voices and opinions, and necessitates the elevation of such voices to national media.

The distinction between national and regional media portrayals of nuclear power was discussed by Interviewee 6, who spoke primarily on the ability of nuclear technologies to solve regional problems, and their effects on the local population:

> Regionally the media understand the benefits that the project can have particularly in a post-COVID economic recovery stance and the importance that it can have on a boost in education and skills . . . nationally I think some of the national media still don’t really take the kind of bigger picture view of the role nuclear has in tackling climate change. I think that they’re not really reflecting and understanding the importance of the role that it can have.

The lack of foresight in media is discussed by Interviewee 6 through the absence of a “bigger picture view”. Especially in the case of “tackling climate change”, which itself lends a sense of urgency and priority to the issues at hand at present and in the future, the narrowed discussions in national media centred around the favourable consequences of nuclear technologies are perceived by Interviewee 6 to be unhelpful in exploring nuclear future multiplicities. Furthermore, Interviewee 6 chose to focus on how the advantages of nuclear power are excluded from narratives in national media, rather than referring to negative or questionable commentary of nuclear power that may be mentioned outright in both regional and national media; from a communications perspective, she expectedly reasoned that foregrounding the benefits of "the project" through the use of social, economic and environmental framing relates to how well the media understand the value of nuclear power. To Interviewee 6, poorly established acceptance of nuclear power in the media can become potentially damaging when circulated amongst the general public, and hence the way she tethers nuclear power to the extensive and far-reaching issue of climate change provides a well-grounded rationale for public nuclear acceptance.

Interviewee 8 spoke on the challenges of publicising views in many of the major news platforms and mentioned that "the nuclear industry is very very well-funded, you know it's got a very strong PR department," adding that "it's not a very fair debate a lot of the time", and expressing that "it's a constant challenge to get your views into the things". He observed that there is an "almost daily drip of good stories" about nuclear power, ones that mainly focus on the benefits and necessity of nuclear power for a 'net zero' climate. On this imbalance, he elaborated:

> Unless there's a sympathetic journalist interested in the story or there's something juicy in the story, that journalists tend to ignore what the other side says and there's a lot of journalists that will take on board what the industry says without question a lot of the time.

According to Interviewee 8, the lack of critical examination of the nuclear industry strengthens the authority of their statements and offers very little leeway in their positioning in the public sphere, allowing for the details in their statements to remain ambiguous and concretising their hegemony in the media. Pete, when elaborating on the nuclear industry's aversion towards participating in publicised debates, remarked that “they shy away from it and I’ve found that it’s a question that they prefer to avoid about the detail and the consequence of having a nuclear power station here”. He highlighted the propensity for the nuclear industry to engage on platforms that serve as advantageous in furthering their narratives, and interestingly called attention to how the industry tends to refrain from reciprocating any substantial engagement when non-industry parties initiate discussions. This preserves the systematic control of how the nuclear industry is represented and reinforces the sustaining and subduing of conflicting voices in the media, reinforcing the existing boundaries between dominant and acquiescent groups.

The alarmist content regularly found in sensationalist coverage of nuclear power in the media was touched upon by pro-nuclear interviewees in order to highlight its potential to construct a skewed perspective of nuclear power to media consumers. In these, emphasis is placed upon the materialities of nuclear power and its heightened risks to the general population, where the physical enters the social by stark imagination. On the commercial incentives of sensationalist content, Kristin remarked:

> A lot of times we get like the more sensational headlines even if it’s like say some valve is leaking that has nothing to do with anything nuclear it’ll be, it’s like ‘massive leak at nuclear plant’. And then that’s the headline and then you have to read a little further like, oh that doesn’t actually have anything to do with nuclear. It’s steam or something.

Here, her interpretation and perception of common media content drew upon the significance of the way structural failures of nuclear sites are amplified through incomplete details, and as Interviewee 5 stated, the resulting imaging and connotations are foregrounded in the public consciousness from the “dangerous and rather edgy, unsafe kind of way” nuclear narratives are often presented in media. Further to this, he stated “we are very conscious that if we had an incident on this site despite the fact we have very little radioactivity . . . the headline in the local paper will be something like ‘fire at nuclear plant”, highlighting the omission of certain levels of detail to generate interest. Kitzinger comments on the tendency of journalists to be “risk junkies”, and notes that sensationalist practices frame the role of ‘official’ information sources as being "purely 'scientific'" [505], thereby assigning to their sources a certain level of trustworthiness. This elevates their authoritative positions and contributions in knowledge spaces in dealing with the somewhat enigmatic characteristics of a nuclear power plant.

The power held by such esteemed sources is accentuated through their direct inclusions in media when statements are incorporated into the content body; Heather spoke of the propensity for nuclear power companies to be the sole pro-nuclear view in journalistic media:

> [They interview] the company and what's going on at the plant and then someone anti-nuclear who you know offers up some opinion about what's going on but there's never like a pro-nuclear because they're like, oh well that's the company ... And the company, you know they're very official and don't necessarily respond [to "negative" statements from anti-nuclear groups] in a way that sounds good to an audience.

Not only are the companies the solitary voice of support for nuclear power in media, their corporate nature heightens the rigidity in their linguistic styles, which Heather observed is often not tailored to convey affective meaning in order to sound "good to an audience". However, the media may not immediately allow for different or imaginative ways of speaking. Facts and figures prevail in media outputs, which are written and broadcast as permanent records of the past and the present, as significant reports that demand a certain degree of officiality. Such limitations control how nuclear discourse is shaped in the media, where the marketisation of news through sensationalism and a lack of scientific training of journalists define who is at the forefront of the pro- and anti-nuclear stances and how they are perceived. The singularity of the nuclear industry as a pro-nuclear voice in media gives substance to Interviewee 8's impression of the unquestioning attitudes of journalists, alongside a multitude of other possible reasons. These include requiring media brevity, intentional portrayal of conflict and a grandness to the scale of opposition, and a likely lack of community-led support groups for nuclear power due to the implementation of nuclear power being primarily a political decision, thus obviating the need for such groups.

With such a responsibility to uphold its reputation in the media, the nuclear industry is additionally guided by public opinion to mitigate the consequences of a faulty reactor site to the greatest extent. Heather remarked, “the company wants the public to think that they’re safe and doing things well”, placing emphasis upon bolstering public support through publicising industrial safety measures. She continued:

> Every little thing that might become an issue to the media, the company tries to address it you know head on. Like someone gets a paper cut and it’s like, oh no an employee’s injured at the nuclear plant [LAUGHS]. So we try not to let people get paper cuts, like that’s how kind of our industry has evolved to be super safe and super, you know like very, lots of good processes and lots of you know things in place to prevent any kind of issues because any issue no matter if it’s significant or impactful or not, you know becomes an issue to the media.

Heather elaborated on the importance of providing reassurance when safety is compromised, and alluded to the extremity of safety measures that also serve to prevent the media from maximising the severity of the issue. In part, the ‘evolution’ of the nuclear industry is necessitated by uncertainty in how the media reframes the problem; whenever issues arise, active communications and procedural implementations become imperative in limiting the media narrative. An alternative way of framing Heather’s comment is that media scrutiny can be useful and positive rather than harmfully sensationalist, which in turn can affect public attitudes and narratives.

The point of media influence on the nuclear industry was also raised by Interviewee 5, who shared with me the challenges of redefining how fusion is related across society. Due to the negative connotations of being termed under the ‘nuclear’ umbrella, the UKAEA proposed a name change from ‘nuclear fusion’ to ‘fusion energy’ in order to distance nuclear fusion from various associations with nuclear weapons and nuclear fission technologies—a key endeavour when STEP is increasingly introduced into public knowledge through the media. Interviewee 5 focussed on the media's choice of wording, noting that "if you see anything printed in the press, then it always says nuclear fusion because they always have called it nuclear fusion", adding that it will "take a long time to work your way round and it may well take ... years" to change how the nuclear fusion industry is known in the "wider consciousness and amongst the media". In describing how the media "always says" and "always have called" nuclear fusion in an explicit way, he alludes to complications in the long lasting associations in labelling technologies. Furthermore, the use of absolutes—by many of the interviewees—when speaking about the media signifies a sense of knowing and familiarity with the way nuclear power is often presented to the public. The media controls how knowledge of a concept, idea, or technology is identified and transmitted throughout knowledge circles[7], cementing themselves as arbiters of knowledge and creating finality in meanings which are then pervaded through social connections. The nuclear fusion industry, in attempting to change public comprehension of nuclear fusion by forging new identities, will contend with the content and perspective of various media outputs and challenge the status quo characterised by the media. Fundamentally, they seek new control in the way mass media fills in education 'gaps', discussed by Wade and Schramm in being central to the knowledge held of general science and science politics [506]; this becomes important in establishing corrected understandings of scientific concepts and technologies in the media.

Interviewees reflected on the scientific literacy of the media, and related this to their perception of how journalists understand as well as misunderstand. In particular, Wade held issue with the scientific knowledge presented in the media, questioning the scientific credibility of journalists—"well they don't know what they're talking about"—and stressed the need for differentiation between science and technology, claiming that "they think that science is rapidly changing. Well science

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[7] I refer to 'knowledge circles' here as the various groups that will invariably hold different levels of knowledge about a specific topic, such as the consumers of a particular type of media.

doesn't rapidly change". As a professor of Physics, Wade's occupation situates him as a generator of scientific knowledge, and so his critical assessment on the need for distinction and accuracy in media comes as a result of his positionality, and may contribute partly towards his view of journalists as scientifically incognisant. Interviewee 5 shared a similar sentiment when discussing the media's understanding of nuclear fusion, stating that "the way the press reports on fusion is pretty accurate because they don't know that much about it". Central to his argument lies the claim that only surface-level details of nuclear fusion can be communicated due to knowledge deficits in journalists. However, what Interviewee 5 is conveying here, compared to Wade's assertion of media incoherency, is how this limiting factor does not necessarily render media reports inaccurate, whereas Wade argues that a lack of understanding amongst media journalists gives rise to faults in the technicalities of science. These contrasting viewpoints both serve to highlight the various ways through which journalists' knowledge influence both media reports and the impacts on the way the general public are informed through them.

Interviewees 5 and 6 separately mentioned George Monbiot, a notable journalist who writes prolifically on environmental and political topics, regularly discussing the gravity of the climate crisis. One week after the Fukushima-Daiichi accident took place, The Guardian published an article penned by Monbiot explaining his reasons for supporting nuclear power, marking a transition from initially being "nuclear-neutral" [507]. Interviewee 6 illustrated this transition as a 'realisation', whilst Interviewee 5 noted that Monbiot's writings on Fukushima were "a little bit different to all the others"; by providing a prominent example of a media figure with a changed viewpoint, atypical of most environmentalist journalists, both interviewees touched upon the seemingly counterintuitive action of journalists adopting a reconsidered stance on nuclear power from technological disasters. In particular, the social reach of journalists like Monbiot due to publishing in well-known publications carries an implication; his writing could potentially assuage public concerns over nuclear technologies, benefitting the interests of Interviewee 5 and 6 and contributing to reassessments of nuclear power in the media.

As we have understood from the interviewees, the duality of nuclear power in the media takes the form of antagonistic and protagonistic portrayals in nuclear stories, which are told in a curated manner through intentionally shaping narratives and catalysing action in organisations and individuals. Cultural shifts in the nuclear power industry are enabled in part through the media's contribution to nuclear discourse, and relationships become intensified. Pivoting to the media's influence on nuclear futures, we are able to establish, from current perceptions and inferences, that the futures of nuclear power are dependent somewhat upon the futures of media through assuming the continued existence of media as a constant institution, as well as their practices. Interviewee 5 suggested that the outcome of future nuclear technologies "would depend on how well promoted it was, how the media portray it", alluding to the sensationalist tendencies of the media. Linguistic effects could also have an impact; Koerner postulates that positive perceptions of nuclear power could be accelerated through the use of simplified terminology and less jargon in media [508]. Altogether, changes in media procedures could affect depictions of nuclear technologies and their characteristic imagery, and so shifts in the dissemination of information pertaining to future technologies may guide their societal integrations differently from past efforts. Making media that speaks of futures—and also with the futures—of nuclear power is a challenging prospect for an institution that has a focus on the 'happening' and the 'now', but by recognising particular journalistic methods in media discourse, this will allow for extra insight into their contributions to nuclear narratives.

In capturing the current events surrounding nuclear power, media journalists effectively document and narrate the past, present, and, doing so, help shape futures of nuclear power, and concretise sentiments during particular moments in time. As futures thinking is dependent upon current and past narratives, it is therefore crucial to explore how past actions and discourse can influence perceptions of nuclear futures. Doing so through the lens of the interviewees' individual understandings allows for contextual insight into their narratives of nuclear power, and allows for a social collective memory to grow.

For instance, Interviewee 6 made mention of the lasting prominence of opposition groups:

> There was an organisation called Shut Down Sizewell that was set up decades ago and I think is probably still running and I think they say very similar things to what opponents would say now about nuclear. I don't think the view has changed really over the years.

Interviewee 6 referenced the "Shut Down Sizewell" campaign, a group that is currently affiliated with TASC due to greatly diminished group size. Here, Interviewee 6 illustrated the perpetuity of opposition to nuclear power, and used the past narratives of the campaign group to express how attitudes and sentiments remain unchanged over time. Similarly, Heather drew upon the past to demonstrate how opposition to nuclear power is able to shape the identity of a nuclear power plant:

> Diablo Canyon is pretty famous. It's kind of home to one of the biggest protest sites. We still have a record for having the most anti-nuclear protesters like in one area for the longest time protesting the building of the plant back in the '80s.

Such entanglements between social action and nuclear materialities have evidently permeated throughout time, and can be considered as emblematic of the temporal preservation of common attitudes and perceptions.

Interviewees tended to use the history of nuclear power as a benchmark for its technological progress. Interviewee 7 observed how initial decisions made by the nuclear industry often overlooked potential technological and material ramifications:

> What's clear is that when we started down the nuclear path in the 1940s in Britain, we were catastrophically bad at managing these facilities. We're lucky that there weren't more issues and now we have this incredibly expensive

> amount of legacy waste, particularly at Sellafield but also elsewhere that we need to deal with.

Here, Interviewee 7 claimed that an element of fate accompanies the usage of nuclear technologies, evoking the notion that the future eventualities of nuclear power are multitudinous in nature. In addition to this, he reflected on accommodating such eventualities in technological and infrastructural designs, stating that "we need to think about all sorts of future eventualities over a very long period into the future when we're designing facilities now". Through his comment on nuclear waste, Interviewee 7 identified the complexities of materials that are inherently intimately connected to the past and futures of nuclear power. He also touched upon gradual attitudinal shifts over time, both socially and in the nuclear industry, stating that "we didn't know in the 1940s about climate change" and that "we've reduced the amount of fossil fuels we burnt otherwise" with new nuclear stations. Here, Interviewee 7 touched upon how emerging social attitudes provided new motivations for the nuclear industry in developing nuclear technologies. However, other interviewees vehemently questioned the nuclear industry's perseverance and continued efforts to fulfil the past determinations of the nuclear industry. For example, Interviewee 8 stated:

> We've tried fusion now for 70 years and got nowhere yet you know, so you know I know it's always there as the Holy Grail ... waste-free energy and copious amounts of it, you know. That's what vision was promised in the '60s really and it never appeared then.

In using metaphorical language to describe nuclear technology, Interviewee 8 sought to add meaning to his argument, and illustratively convey his views on the past, present, and future of nuclear power. In particular, his commentary conveyed how emotive and attitudinal elements such as trust and belief accompanied the "promised" vision, which was heightened due to the magnitude of meaningful material potential. In subjectively connecting with the history of nuclear power, interviewees were able to align their personal narratives to the material and social entanglements of nuclear power.

Wade used the past as a comparator period in our interview, claiming that for the nuclear industry currently, “we are in a really exciting situation now. It’s like 1900 in the car industry”, implying burgeoning technological development and sharply increasing industry productivity. Wade also reflected upon the achievability of nuclear technologies in the journey from developments in nuclear history to the present day, stating:

> All the things I’ve done technically in physics have always been things which other people thought were impossible and if you do work on an impossible project then it cuts down the competition because you can really make a difference because other people have said, it’s impossible.

As Wade alluded to in his interview, by “[making] a difference”, the scope of shared futures is widened and made more accessible. Interviewee 5 shared similar sentiments, stating that as to “why [I am] still in it and I’m doing what I do, then it is to make the world a better place in the future”. Such shared futures also demonstrate the intricate entanglements between material impacts and the societal pathways that lead to these futures.

On visualising the role of nuclear power in technological futures, many of the interviewees referenced social behaviours evolving in tandem with energy usage and the progression of nuclear technologies. For example, Interviewee 5 was adamant in his opinion that “nuclear and fusion in the longer term have to have a role otherwise society and the way we live our lives has to change dramatically and I don’t think people will find that very easy to accept”. Some interviewees focussed on specific behaviours, such as Interviewee 6, who offered a consumer and energy delivery-driven perspective:

> We’re going to electrify more of our systems. More of our transport system needs to be moved to electrics so we’ll have more cars on the road that are electric and we need more reliable low carbon generation to deliver on that ambition.

Heather shared a similar view to that of Interviewee 6 in terms of providing energy to enable the mass electrification of societal systems to be expedited, and identified nuclear power as the catalyst for these social changes:

> If we're going to electrify transportation and build more electric cars, if we're going to electrify residences, you know stop using natural gas for heating and water heaters and dryers and ovens, like we need a lot more clean energy and there's no other way to do it than with nuclear.

Kristin concurred, and envisioned the global distribution of electricity from nuclear sources as a driver of social equity: "I see nuclear as being a key if we want to provide clean electricity across the globe at a price that all countries can afford and not just the most wealthy among us". Kristin's position on nuclear energy materials as a social equaliser contrasts in perspective to the social inequalities that have emerged from the human-material entanglements of nuclear power, such as the "slow violence" of nuclear environments [163] and the coloniality of the nuclear materialities as described in Chapter 1.

Interviewee 7 also reflected on possible energy futures:

> If somebody could convince me that there was no nuclear in the future energy mix and that we could have a net zero energy system that was sustainable and didn't cause all sorts of other environmental impacts, then I'd be delighted. But I think probably we do need some nuclear in the mix.

Here, Interviewee 7 indicated that the necessity of nuclear power as a current and future energy source is in part an avoidance of undesirable alternative futures, where an over-reliance on fossil fuels would bring adverse social impacts. To a somewhat greater extent than Interviewee 7, Wade envisioned the role of nuclear power in far futures:

> All the energy for the food that we eat in 150 years time I expect will come essentially from nuclear power. We will not be powered by the sun. We will not depend on the weather or the geographical latitude. You can have strawberries at the North Pole. You can have them buried underground. If the environment becomes impossible to live in because it gets too hot or too humid, we can go underground. But with nuclear power stations we could have all our food and everything. We've got a long way to develop all that but there is the energy for it. We would not depend on the sun anymore.

In a virtually science fiction perspective, nuclear power featured heavily in Wade's imaginary narrative. Here, nuclear technology would enable barriers to be overcome, and facilitate the continuance of current social practices, avoiding any behavioural adaptations in a resource-scarce society.

For other interviewees, it was more difficult to envision the role of nuclear power in energy futures. For example, Janet remarked that "it's hard to have a crystal ball". However, she was nevertheless concerned about handing the waste "on to generations yet unborn". By projecting current concerns and impacts onto a yet-to-exist, yet conceivable future generation, this then motivated moral reflections from interviewees. When discussing nuclear waste, Interviewee 7 expressed that "we have to do the right thing for future generations", and suggested that futures thinking methods are required for this:

> In 50 years time technologies that might deal with waste in different ways or use waste as an energy source, may appear but of course we don't know that. So I think we always have to keep scanning the horizon and be respectful of future communities but we have to try and do the right thing now rather than defer it to say, well that can be their problem.

In response to my question around a potential technological solution that would prevent accidents on the scale of Fukushima Daiichi, Heather correctly presumed that the crux of this question was a representation of ATFs, and emphasised the impacts of such technologies on public relationships:

> I wish we didn't have to have a solution like that but yeah it'll definitely help in people's minds you know that something like [an accident] can't happen. That's a great thing to be able to say and yeah I wish we didn't have to focus on that so much but I mean yeah it's expensive also and when something goes wrong, if you have to clean up you know a reactor like the Three Mile Island reactor and that was very sad and we want to protect all clean energy investments but yeah definitely in terms of public opinion it'll be huge.

Curiously, instead of dismissing this hypothetical technology, Interviewee 8 appraised it through an evaluation of its economic uncertainty:

> That's a feasible idea. I mean it sounds great in theory. I'd like to see it happen in practice and be proven really as well, and again how expensive will that technology be and so forth really? There's a lot of unknowns in that.

By considering the material and social costs of a technology that was hypothesised to solve particular problems in the industry, interviewees were able to engage with speculative futures thinking and explore their personal reactions to a potential technological implementation, albeit at a high level of understanding.

Many interviewees, upon being asked to share their message for a society living in an unspecified future, offered pieces of advice that encapsulated their personal attitudes and perspectives towards nuclear power. For example, Heather encouraged the society of the future to accept and adopt nuclear power to enable them to reallocate the focus on finding energy solutions towards other societal matters:

> Don't be scared, this is the key to our future and I think the more we give people plentiful clean affordable energy, the better quality of life we'll have and the better we'll be able to focus on other things instead of like squabbling over resources. You know if we have plentiful energy then that changes a lot of things for human society in terms of you know our ability to focus on other technologies that you know advance food production or you know populate birth control or you know huge–, there's lots of issues on our planet and if we could just not be scavenging for clean energy, you know like there's a lot of effort that goes into that and a lot of people's brainpower and yeah let's fix some other things also.

Heather's hopes of a more technologically advanced and socially beneficial world for people living in future societies also placed emphasis on the people who enable the changes to be made through driving changes in nuclear power technologies. In a similar vein, Interviewee 5 lamented the increased distrust of experts in nuclear power, and therefore to a society of the future, he would say "science is the way out of all this. It has to be and therefore that would be my message. Trust it, trust the scientists". Taking a more cautious stance, Interviewee 7 advised diverging from nuclear power:

> You know it was done of its time, it was not done particularly well ... If you have mastered other ways to generate electricity that are better, then absolutely embrace those, or whatever energy source you need in the future you know.

Pete shared a succinct message in the form of a blunt and idiomatic expression: "don't touch it with a bargepole". Similarly, Interviewee 8 saw no role for nuclear power in a future society, with the reasoning that "it comes down to cost as much as anything". His message was, like Interviewee 7's, rather reflective as he considered the social impacts of past decisions:

> Don't do it [LAUGHS]. I think if I was sending a message to people of the future that says, what a mess we've made of the past really you know ... we've made a mess of it really all for the sense of getting something powerful.

Common to all the interviewees' messages for a future society was an overall endeavour to impart technological awareness or implement change to engender a net positive social impact. Overall, good intentions underpinned the interviewees' messages to a future society—there emerged a shared theme of some kind of societal progression and improvement, whether that be using nuclear power as a vehicle to better societies, or eliminating nuclear power altogether.

Interviewees also discussed the length of time associated with creating and implementing nuclear technologies. For example, Interviewee 7 argued that when designing nuclear spaces and infrastructure, anticipating and planning for nuclear timescales would increase the efficiency of nuclear power processes:

> If we're going to build a geological disposal facility, arguably another generation of nuclear power is not going to massively change that you know. If you've got a GDF, the waste from that next generation can go into that as well.

Others, such as Interviewee 5, spoke on the difficulties with becoming known in the "wider consciousness" as 'fusion energy' rather than 'nuclear fusion', noting that "it will take years and years and years I'm sure but there is a confusion, so people do call it nuclear fusion". The challenge presented here of engineering a competing understanding of nuclear fusion in spite of established knowledge highlights how nuclear narratives can persist through time. Wade generally agreed, stating that "changing the way people think ... is going to take a generation".

Kristin focussed more on the passage of time necessitating innovation; she highlighted the pathways of other technological innovations to justify the development of new nuclear technologies such as ATFs:

> With accident tolerant fuel and other innovations I think those are really important because we can't just be stagnant technically you know. No industry that progresses and continues to be successful is stagnant, right. Like we're not all using you know like iPhone 6's any more. They keep making new models and nuclear needs to keep up and show that it's advancing as well.

However, she caveated her view with the need to use current nuclear technologies as a method of extending the timeline to deliver new nuclear technologies, thereby enabling alternative nuclear futures:

> We can't just stay static with our technology but I think it's important not to have our eyes solely fixed on some future solution and then ignore the really great solution that's right in front of us now. So part of what Heather and I have been for is to keep existing nuclear plants operating while we make space and time for those future technological innovations.

For Kristin, as well as other interviewees, intergenerational thinking evidently plays a significant role in advocating for social equity, allowing for reflective insight into changes to current regimes and systems.

Many interviewees commented on the length of time associated with nuclear power developments. For example, Pete commented on the disturbance that the local community near Sizewell C would experience:

> There is a general upsurge of opposition to what's going on in Suffolk and it's not just from the opposition groups, it's from ordinary people who are facing 12 years of disruption in their lives, 12 years of noise, 12 years of dust, light pollution and disruption to their way of life.

To express the gravity of these changes, Pete reiterated the timescale of the disruption, and emphasised that locals external to TASC also comprehended the ramifications and wide-reaching impacts as a result of Sizewell C, suggesting the unpopularity of this development. He extended his concerns to nuclear fusion, commenting on the potential costs incurred as a result of development:

> I don't know a great deal about fusion, I'll be honest with you. In my opinion we are going down a route which is so manifestly complicated and so manifestly unproven that we've been trying for fusion for years and years and years and

> we haven't actually managed to make it work and why we keep spending millions and billions of pounds trying to develop fusion is beyond me. I don't understand what the attraction of it is you know. It's a technology which is proving like the Holy Grail.

On the cost of nuclear fusion, Interviewee 8 echoed Pete's view, arguing that "there's a lot of money being spent on something that might never actually succeed". Interestingly, Pete used the same metaphorical comparison as Interviewee 8 ("Holy Grail") when discussing nuclear fusion. More than just a metaphorical comparison, it is also an invocation of a very powerful, cross-cultural, ancient narrative, which highlights how the discourse of nuclear power is supported by narrative understandings. From this, it can be seen that a shared language in terms of descriptors and depictions of nuclear power technologies is often a representation of the commonalities between people who identify with shared values, such as in activist spaces.

On the materialities of nuclear power, Interviewee 7 remarked that "a bit like climate change, the challenge for nuclear is the long time scales it operates on", and added:

> If you're saying that, you know Sellafield will take 120 years to decommission and then we'll build a GDF which will–, well overlap, we'll build a GDF that will take 120 years to construct and fill and then the waste will need to be safe for 300 thousand years which is more than humans have been on the planet, then these are really hard things to do.

Much like Kristin, Interviewee 7 also commented on the constant technological improvement of industries in the context of designing technologies that will be superseded: "the waste in GDF [is] radioactive for 300 thousand years, as I said that's beyond human society. Most computer records only last, you know they're only usable for 20 years before technology moves on". Similarly, Interviewee 8 discussed the limitations of human expertise and understanding through time, citing the impermanence and evolution of knowledge as factors of weakness of nuclear power:

> That reactor that's 43 year old was built in the 1970s when technology was advanced but not as advanced as where we are now really you know. So it suffers from the issues of lack of knowledge that would have been then.

He also mentioned the insufficient amount of time for any proper implementation of nuclear power, especially concerning the impacts of the climate crisis requiring urgent action:

> We have to keep moving up faster and faster and faster because the imperative of temperature rise is showing us that really you know. Melting ice caps in the Antarctic, in Greenland and record temperatures in Siberia and all over the world means we just have got to get on with it really … we have to deal with climate emergency issues now, this is still a future technology, at best 20 years away. It's almost always 20 years away. You know there's some suggestions of improvements but you know there's still an awful long way to go to make it commercially viable. So in our view, get on with practical, you know alternatives rather than spending billions on something that might never happen.

Here, Interviewee 8 shared an outcome-focussed view, where "alternatives" in the form of cheaper renewable energy sources would constitute the optimal plan for change in the form of action. In contrast, in Interviewee 8's view, the strategy-driven approach is too slow to deliver, which appears to be inadequate for the globally-reaching impacts of the climate crisis.

Ultimately, this thematic cluster highlights the way discourse and narratives of nuclear power can evolve in social contexts, drawing on the spatial and temporal entanglements between the society and nuclear materialities. From media narratives, to examples of futures thinking, the interviewees shared their own interdisciplinary perspectives and demonstrated the social influence of nuclear technologies through time, essentially unravelling and creating further narratives and space for future discourse.

3.6 Conclusion

Through these four thematic clusters, the emergent themes in the interviews have been consolidated and exhibited through logical compilations of interview extracts. Across all four thematic clusters, the interviewees showed both commonalities and divergence of opinions. Nevertheless, all interviewees were able to reflect on the material and social impacts of nuclear power, and the futures that may materialise as a result of different decisions.

Overall, the interviewees, through the interviews, have demonstrated the meaning of humanity; by striving to live together on our materially damaged planet, we bring our different perspectives of the world and our different values into the conversation around nuclear power, and it therefore remains a challenge to navigate our nuclear futures. A clear requirement for any future involving nuclear power is direct and explicit dialogue between all parties, and a shared understanding of common goals, despite differing objectives.

My analysis of the narratives around nuclear power has shown that there is interest towards technological developments in nuclear power, such as the role of ATFs in ensuring a safer mode of energy generation. Therefore, in the following Chapters, I explore some technical aspects of ATFs to gain insight into where they are along the pathway to deployment.

In this chapter, I explored the attitudes and sentiments of nuclear power to discuss perceptions and narratives around nuclear technologies. The findings from this chapter can be used in part for the justification of the work in the next two chapters on nuclear materials science, which follow this chapter, as can be seen in Figure 3.4. In the next chapter, I present my quantitative research on diffusion in hypo-stoichiometric UN to begin my investigation into thermophysical behaviour in reactors.

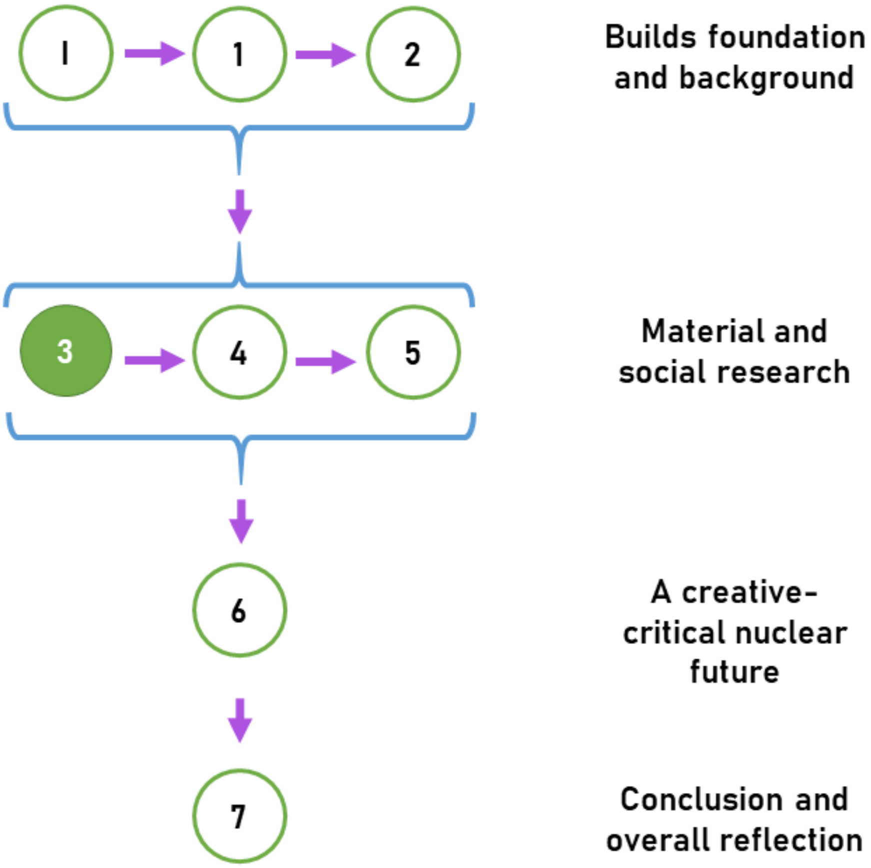

Figure 3.4: A map of the thesis structure. The chapter that we are in now ('3') has explored narratives and attitudes around nuclear power.

Chapter 4

Diffusion in hypo-stoichiometric UN

This work can be found in: J. J. Li and S. T. Murphy, “Diffusion in hypo-stoichiometric uranium mononitride”, *Progress in Nuclear Energy*, vol. 142, p. 103 995, 2021 [509].

In the previous chapter, I explored nuclear discourse and narratives through qualitative research, and developed thematic clusters around nuclear power. In this chapter, I use molecular dynamics simulations to explore diffusion in hypo-stoichiometric UN, to explore the thermophysical properties of UN further.

4.1 Introduction

Before UN can be widely deployed in reactors, it is essential to understand its fundamental properties and to be able to predict how these are likely to evolve during operation. While there has been some effort to characterise UN, there is still significantly less available data than for UO_2. Hayes *et al.* have presented experimental values for the lattice parameter as a function of temperature and determined associated linear thermal expansion coefficients for UN [510–516]. Additionally, Hayes *et al.* have collated experimental values for the specific heat capacity and enthalpy as a function of temperature [515, 517–525].

Of particular interest is the mobility of the intrinsic uranium and nitrogen species in the crystal matrix, as this is expected to strongly influence the segregation of fission products. For example, iodine diffusion in UO_2 occurs on the oxygen sublattice [258, 526] and the nitrogen sublattice in UN may act in the same way. This is significant because iodine can cause stress corrosion cracking of the fuel cladding [527, 528]. Holt and Almassy measured diffusion using single UN crystals in an α-particle activation study, and observed that for a temperature range 1900 – 2300 K, the mobility of nitrogen atoms was greater than that of uranium atoms [529].

Experimental activation energies for nitrogen diffusion in UN range between 1.25 eV and 4.20 eV [530, 531]. The lowest energy processes are thought to correspond to diffusion along the grain boundaries. Within fuel grains, the nitrogen interstitial mechanism is thought to dominate in hypo-stoichiometric conditions, i.e. UN_{1-x}, with energies ranging from 2.44 eV and 2.726 eV [529–531]. However, the exact stoichiometry of the samples studied is uncertain as the authors did not state this.

This section discusses, in detail, the use of MD to examine how the introduction of nitrogen deficiency influences the thermal expansion of UN and diffusivity of nitrogen and uranium.

4.2 Methodology

Simulation supercells were constructed from 15×15×15 repetitions of the UN unit cell, as shown in Figure 4.1 [532]. The resulting supercell of 2.7×10^4 atoms combined with periodic boundaries enables a sufficient description of the infinite crystal [240], as it mirrors the relatively expansive distance in a real crystal. As discussed in chapter 1, the UN lattice is able to accommodate a deficiency of nitrogen at high temperatures. Therefore, to represent this hypo-stoichiometric UN, antisites and nitrogen vacancies were randomly introduced, independently, into the simulation supercells using Atomsk [86, 242]. From the phase diagram [84, 85], it can be seen that UN is able to accommodate a nitrogen content ranging from 48 – 50%, therefore we remove up to 2% of the nitrogen atoms.

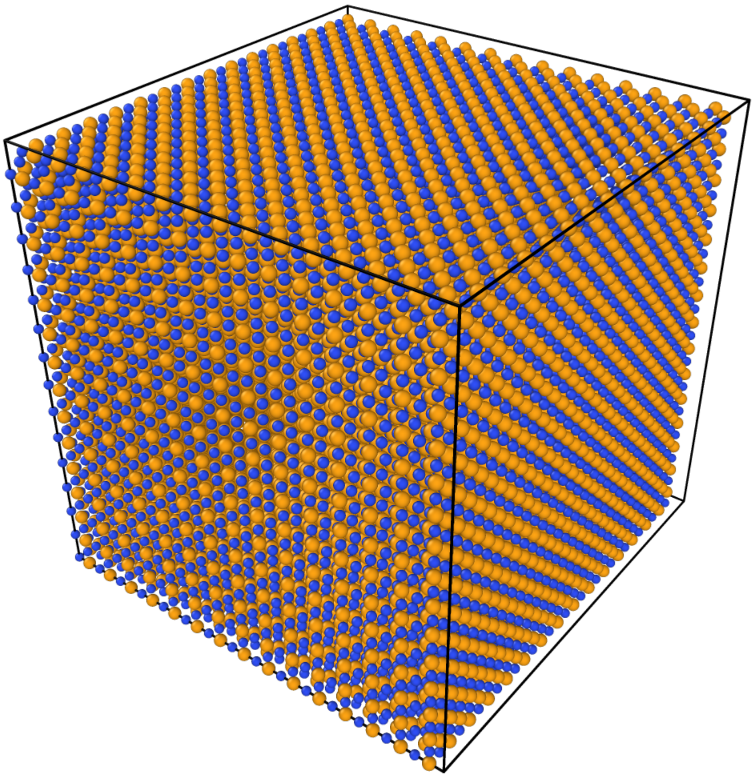

Figure 4.1: The simulation supercell of UN, containing $2.7{\times}10^4$ total atoms from 15×15×15 repetitions of the UN unit cell. The orange and blue atoms represent U and N atoms, respectively.

The UN ADP developed by Tseplyaev and Starikov was used to describe the interactions between the U and N atoms in the UN lattice [251, 252]. In verifying that this potential is able to correctly reproduce empirical observations, the energy minimisation of the UN unit cell results in a lattice parameter of 4.81 Å which compares well with an experimental lattice parameter of 4.89 Å at 53 K [533]. Furthermore, this potential has been shown to reproduce the phase transformation from $Fm\bar{3}m \rightarrow R\bar{3}m$ that occurs at 35 GPa [252].

In order to evaluate the mobility of U and N in the system, the MSD was calculated for each element using equation 2.52. Then, from plotting the diffusivities against $1/T$, the activation energies were determined using equation 2.53. For these simulations, simulation supercells were initially equilibrated under isobaric conditions and at the temperature of interest for 5×10^4 time steps, where a single time step incremented by 1 fs. In this work, as well as in Chapter 5, the Nosé-Hoover thermostat is used for a canonical ensemble, the Nosé-Hoover barostat is used to control the pressure of the simulation. During this equilibration period, the Nosé-Hoover thermostat and barostat were applied with relaxation times of 0.1 ps and 1 ps, respectively[1]. Following equilibration, the supercell transitioned into a microcanonical ensemble for calculation of the MSD. The MSD was calculated over 5×10^4 time steps for simulation supercells containing vacancy defects. For the perfect supercells and those containing antisite defects, the MSD was calculated over 1×10^6 time steps for improved statistics due to the lower level of diffusion expected. Simulations were repeated five times in order to investigate different random arrangements of defects, and the standard deviations of the values from these repeated simulations were used for the error bars.

4.3 Results and discussion

4.3.1 Lattice parameter and thermal expansion

Simulations were performed across a wide temperature range. The lattice parameters for stoichiometric and hypo-stoichiometric UN are plotted as a function of temperature for nitrogen vacancies in figure 4.2, and for antisite defects in figure 4.3. Also included in figures 4.2 and 4.3 is the experimental data of Hayes *et al.* [510]. Immediately obvious from the plots are an off-set of approximately 0.07 Å ($\approx$ 1.4%) between the experimental and simulation data. This level of discrepancy is not unusual for simulations using empirical pair potentials. Despite this discrepancy, the trends in the simulation results demonstrate excellent agreement with the experimental data. All sets of data show that there is a roughly linear increase in

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[1] These values were chosen to prevent large fluctuations in pressure and temperature whilst avoiding long equilibriation times.

the lattice parameter in the range 100 – 2000 K, and that the rate of increase is larger at higher temperatures.

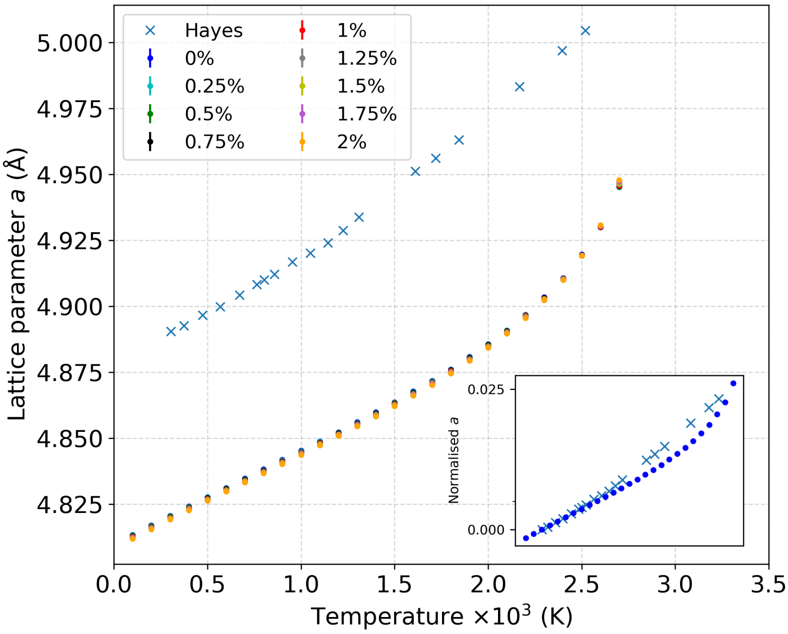


Figure 4.2: Lattice parameter a of UN varying with temperature at various hypo-stoichiometric values due to nitrogen vacancies. The experimental values collated in Hayes *et al.* [510] are also denoted here. The behaviour is approximately linear between 100 – 2000 K for the MD data. The inset plot demonstrates that the simulation sufficiently captures the basic material physics. The error bars are too small to see.

The agreement between the experimental and simulation results is supported by comparing the linear thermal expansion coefficient (LTEC), α [272], which is defined as the fractional change in length of an isotropic material as described by Eq. (4.1) [534]:

$$\Delta L/L = \alpha \Delta T, \tag{4.1}$$

where L is the initial length of the material and ΔL is the change in length. From the simulations, an LTEC value of $(7.78 \times 10^{-6} \pm 1.91 \times 10^{-9})$ K^{-1} was found for a defect-free supercell resulting from the nitrogen vacancy runs, and a value of $(7.78 \times 10^{-6} \pm 5.50 \times 10^{-9})$ K^{-1} was determined for a defect-free supercell from the antisite defect runs. These values compare well with an experimental value of 7.5×10^{-6} K^{-1} across the same temperature range [252, 510, 517, 535, 536]. It is

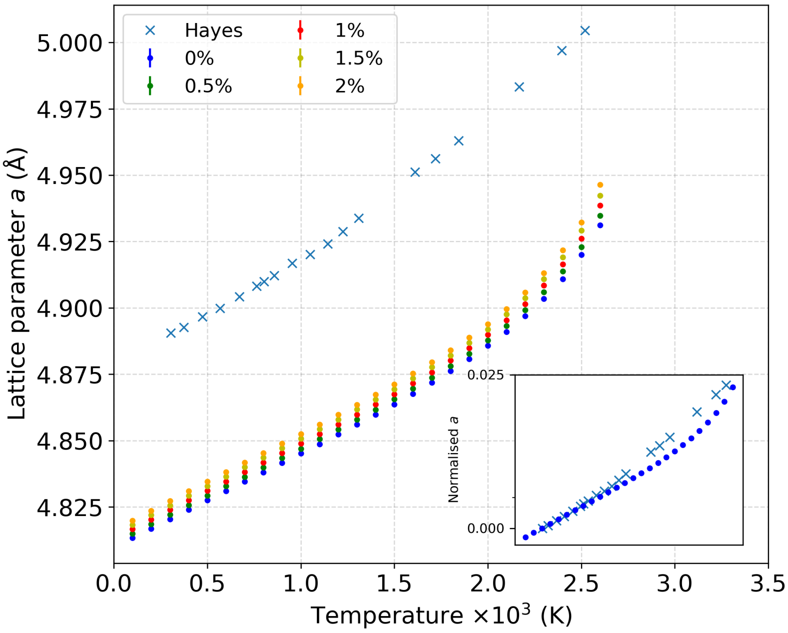


Figure 4.3: Lattice parameter a of UN varying with temperature at various hypo-stoichiometric values due to antisite defects. The experimental values collated in Hayes *et al.* [510] are also denoted here. The behaviour is approximately linear between 100 – 2000 K for the MD data. The inset plot demonstrates that the simulation sufficiently captures the basic material physics. The error bars are too small to see.

noted that these values show significant deviation ($\approx 20\%$) from that obtained by Tseplyaev and Starikov [252]. This discrepancy may have been due to the difference in the ranges of values chosen in the calculation of the LTEC.

Also evident from figure 4.2 is the almost imperceptible change in the lattice parameter due to the inclusion of non-stoichiometry at all but the very highest temperatures. To examine this more closely, the relative change in volume between the non-stoichiometric and stoichiometric lattice parameters are plotted in figures 4.4 and 4.5 for the nitrogen vacancy and antisite defect cases, respectively.

Figure 4.4 shows that there is an almost linear decrease in the lattice parameter as the vacancy concentration increases, although the magnitude of the change decreases very slightly with temperature up until 2500 K. At this point, there is a sudden increase in the lattice parameter and there is evidence of diffusion oc-

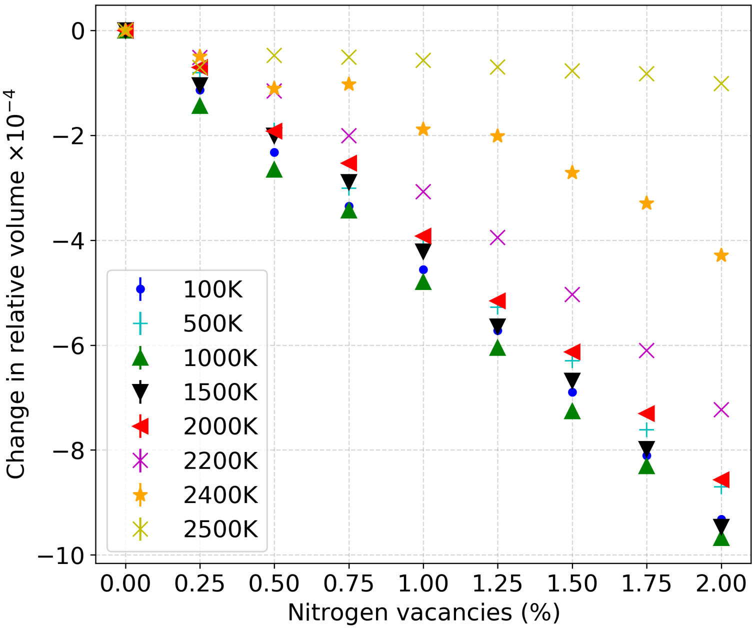


Figure 4.4: The change in volume relative to the volume of a perfect cell at each temperature for a supercell containing nitrogen vacancies. The error bars are too small to see.

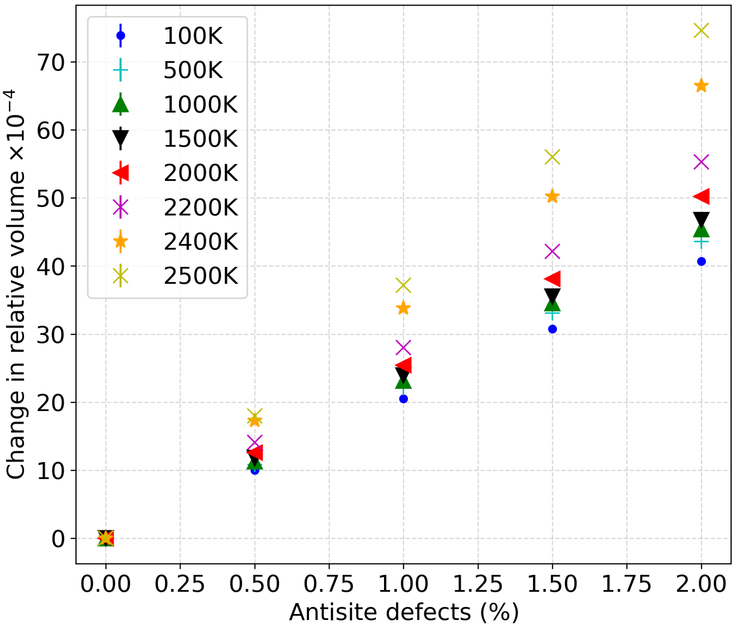


Figure 4.5: The change in volume relative to the volume of a perfect cell at each temperature for a supercell containing antisite defects. The error bars are too small to see.

curring in the simulation supercell. It was also found that there is no distinctive trend between LTECs and the concentration of nitrogen vacancies, indicating that hypo-stoichiometry has a minimal effect on the expansion of UN. Figure 4.5 shows an almost linear increase in the lattice parameter as the amount of antisite defects increase. The data for 2500 K shows a larger increase in the lattice parameters than the lower temperatures due to the atoms possessing more energy in order to be able to diffuse through the lattice.

Prior experimental data showing the relationship between lattice parameter and the degree of non-stoichiometry is limited. Troć investigated the effect of nitrogen composition on lattice parameter and observed a decrease with an increasing amount of nitrogen interstitials at temperatures of 94 K and below [537]. In this work, lattice expansion was observed for increasing hypo-stoichiometry at temperatures above 2500 K, with lower temperatures showing lattice shrinkage for this at lower temperatures. However, Troć studied hyper-stoichiometric UN, whereas this work focuses on hypo-stoichiometric UN; these different regimes may correspond with different lattice expansion behaviours. Understanding this behaviour is important in a reactor context as fuel expansion in an accident scenario may exacerbate the situation as the likelihood of a cladding breach occurring due to fuel pressure is increased.

4.3.2 Diffusion

Intrinsic diffusion in UN was studied in the temperature range 2300 – 2700 K for supercells containing nitrogen vacancies and 2300 – 2600 K for supercells containing antisite defects only. Only these higher temperatures were considered as, due to short simulation times and small supercells, it was not possible to observe statistically significant amounts of diffusion at lower temperatures. However, as the process is Arrhenius-like, the activation energy should be similar at low temperatures, particularly when nitrogen deficiency is present. Figure 4.6 shows the MSD for both uranium and nitrogen as a function of time at 2500 K in a supercell containing 1.5% nitrogen vacancies. In figure 4.6, the linear increase in the MSD for nitrogen with time indicates that nitrogen is able to diffuse through the system at this temperature. By contrast, figure 4.6 shows that uranium appears to be relatively immobile even at these high temperatures.

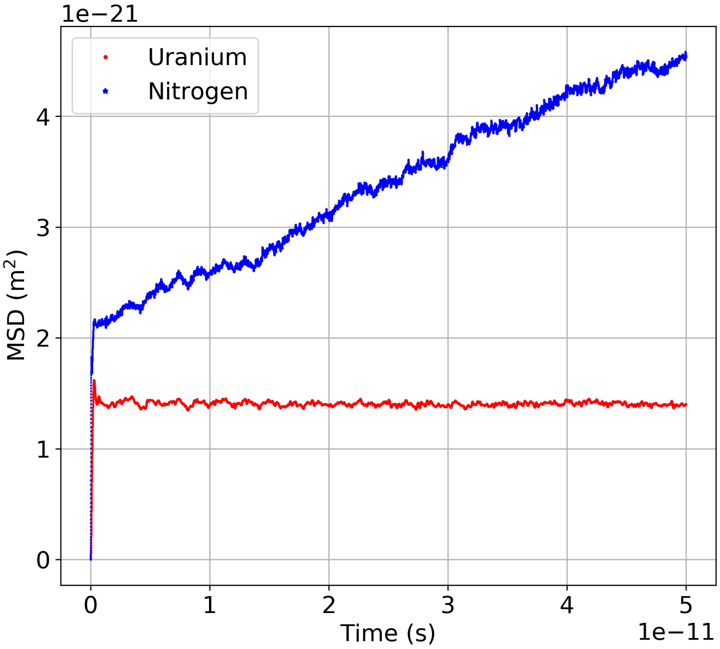


Figure 4.6: A plot of MSD as a function of time for a temperature of 2500 K, with 1.5% nitrogen vacancies introduced into the lattice. Error bars are present, though they are too small to be visible.

The logarithmic diffusion as a function of inverse temperature was examined for nitrogen with different UN hypo-stoichiometry, and is shown in Figure 4.7 for nitrogen vacancies, and Figure 4.8 for antisite defects. As the MSD data for nitrogen atoms presented a linear trend, the method of least squares was applied to fit the nitrogen diffusion points according to [538]:

$$m = \frac{\sum_i (x_i - \bar{x}) y_i}{\sum_i (x_i - \bar{x})^2} = \frac{\sum_i x_i (y_i - \bar{y})}{\sum_i x_i (x_i - \bar{x})}. \tag{4.2}$$

These results can be compared to diffusion plots from experiment as reported in Butt and Jaques [530] and Matzke [531]. For a perfect supercell, the diffusivity values were found to be in a similar range; a difference by an order of 10^2 can be

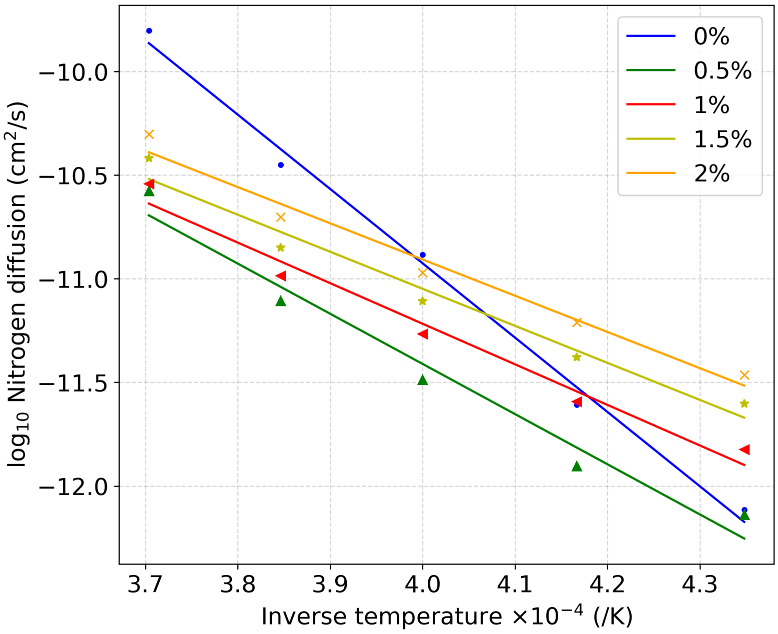


Figure 4.7: The logarithmic diffusion of nitrogen as a function of inverse temperature in a supercell containing nitrogen vacancies, with least squares fitting applied. The percentage of nitrogen vacancies is indicated in the legend. The error bars are too small to see.

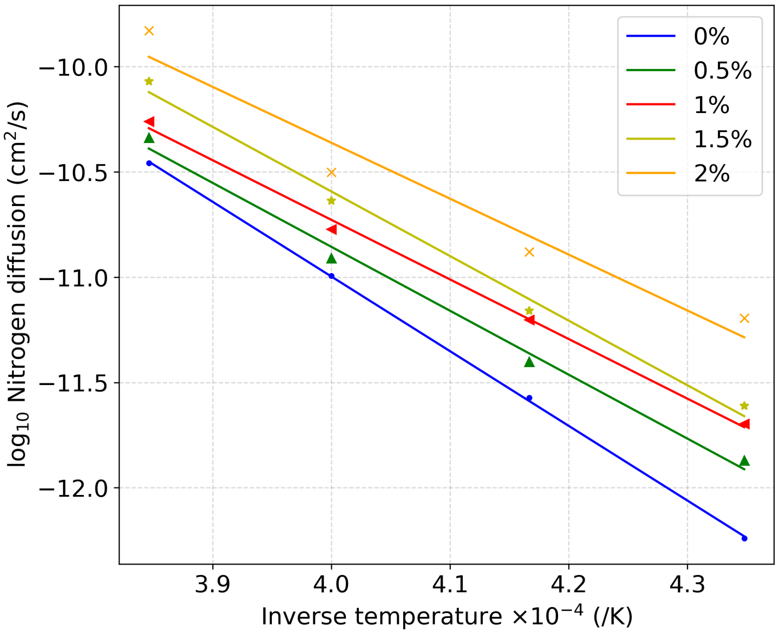


Figure 4.8: The logarithmic diffusion of nitrogen as a function of inverse temperature in a supercell containing antisite defects, with least squares fitting applied. The percentage of antisite defects is indicated in the legend. The error bars are too small to see.

seen between the values reported here and those reported in Matzke and Butt and Jaques. A variation of pressures may have caused this; quasi-stoichiometric UN was studied at 0.1316 atm by Matzke. However, the specific sample details were not reported, so a difference in the make up of the crystal may also have influenced this disparity.

With the gradients of the lines in Figure 4.7 and Figure 4.8 corresponding to the activation energies of the different systems, it is observed that most of the gradients, aside from the perfect supercell for the nitrogen vacancy case, are visibly similar, signifying similar activation energies for these systems. In Figure 4.7, the gradient for the perfect supercell is steeper, which indicates a higher activation energy. This increased activation energy arises due to a lack of defects that can mediate the diffusion process in the perfect cell. The activation energies calculated using the gradients produced by the fit and equation 2.53 are displayed in figure 4.9.

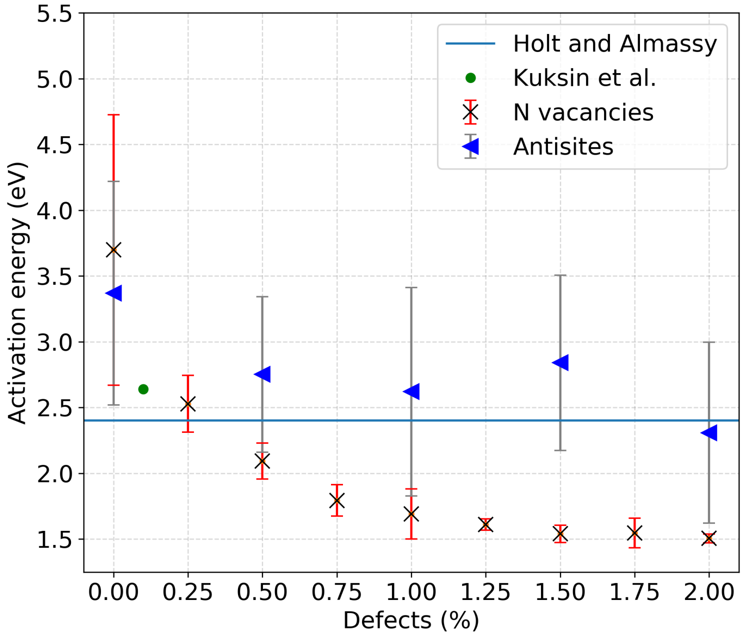


Figure 4.9: Nitrogen activation energies for each considered UN hypo-stoichiometry, compared to nitrogen vacancy experimental data from Holt and Almassy [529] and theoretical data from Kuksin *et al.* [539].

Figure 4.9 suggests that there are multiple regimes present in the data. In stoichiometric UN, there are high corresponding nitrogen activation energies of around 3.5 eV with a relatively large error due to the relatively low levels of diffusion observed. As the concentration of defects is increased, the activation energy generally decreases, as it is easier for nitrogen diffusion to occur through defects than a defect free lattice. For higher degrees of hypo-stoichiometry, the nitrogen activation energy decreases to approximately 1.8 eV for supercells containing nitrogen vacancies, and approximately 2.6 eV for supercells containing antisite defects; this could be indicative of defect clustering, which could have an impact on the diffusivity.

An activation energy of 2.64 eV was determined for a UN sample containing 0.1% of nitrogen vacancies from previous MD simulations by Kuksin *et al.* [539], which agrees with the results presented in Figure 4.9. A study by Cooper *et al.* has found that the single point defects V_{N} and V_{U} have activation energies of 2.98 eV and 3.40 eV, respectively—however, these values are for individual vacancy hops, whereas my results represent the collaborative mechanism of diffusion in the lattice. Experimental values of the activation energy for nitrogen were determined by Holt and Almassy [529]. Unfortunately, the exact level of non-stoichiometry is not reported, thereby making comparison with the simulations difficult. Figure 4.9 shows that both diffusion mechanisms studied exhibit similar activation energies to that of Holt and Almassy [529], but at different degrees of hypo-stoichiometry. At small deviations from stoichiometry (∼0.25%) the vacancy mechanism has an activation energy that is closer to the experiment. However, at all larger deviations the antisite results are in good agreement with experiment.

No evidence of a superionic transition (such as discontinuities in the lattice parameters or specific heats) was observed in the simulations. Therefore, diffusion is thought to be facilitated by the thermal creation of defects in the stoichiometric and antisite containing samples and the movement of the existing defects in the vacancy containing supercells.

4.4 Summary

Thermophysical properties of hypo-stoichiometric UN have been computed using MD simulations and analysed. The lattice parameters were found to be largely unaffected by the introduction of hypo-stoichiometry into the lattice. The average activation energy for nitrogen in stoichiometric UN was found to be 3.54 eV, whereas for higher degrees of hypo-stoichiometry, the activation energy decreases. If the non-stoichiometry is accommodated by vacancy defects the activation energy decreases to approximately 1.8 eV. However, accommodation by antisites results in a reduction to 2.6 eV. These values compare with an experimental value of 2.45 eV, although the exact stoichiometry of the sample is unknown. Previous work suggests that the potential predicts that the antisites are the thermodynamically most favourable process for accommodating hypo-stoichiometry and so are the dominant defects. The agreement between the activation energies calculated in supercells containing antisite defects and the experimental value also supports this hypothesis. This study provides a validation of material properties of UN that have been previously studied, and further material behaviours of UN can therefore be explored.

In this chapter, I probed the thermophysical properties of UN through looking at diffusion in hypo-stoichiometric UN. In the next chapter, I explore the behaviour of the fission product xenon in the UN lattice to see how fission gas bubbles interact with the lattice, which builds upon the findings in this chapter, as can be seen from Figure 4.10.

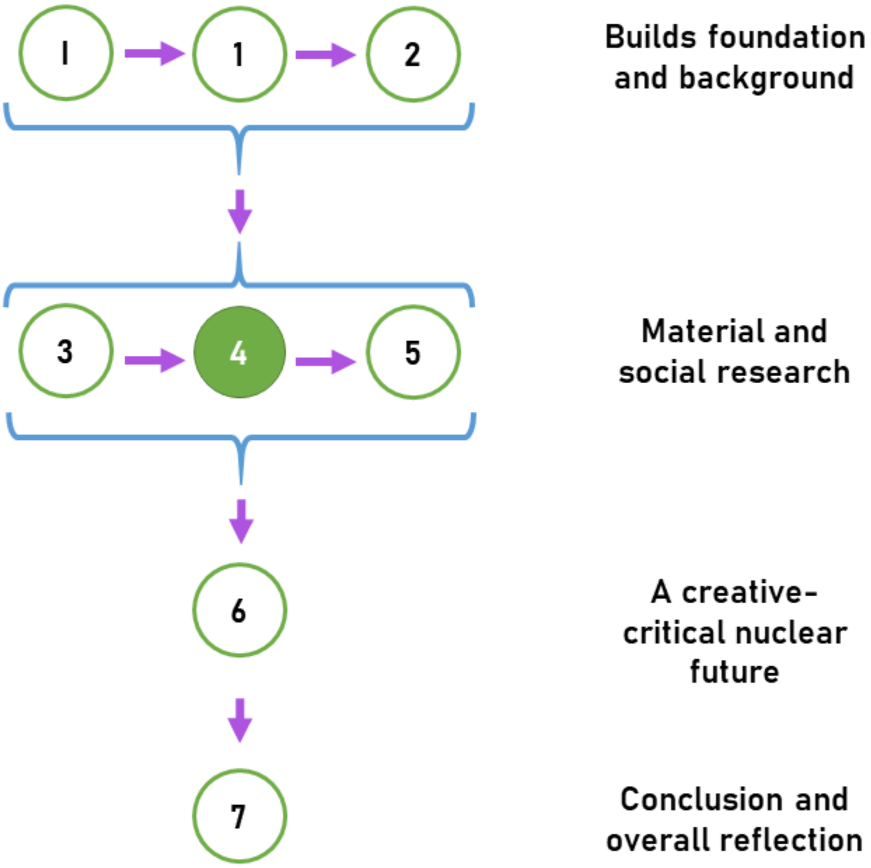


Figure 4.10: A map of the thesis structure. The chapter that we are in now ('4') has explored diffusion in hypo-stoichiometric UN.

Chapter 5

Xenon bubbles in UN

This work can be found in: J. J. Li, N. Zagni, W. D. Neilson, R. L. Gray, and S. T. Murphy, "The incorporation of xenon at point defects and bubbles in uranium mononitride", *Journal of Nuclear Materials*, vol. 586, p. 154656, 2023 [540].

In the previous chapter, I explored the thermophysical properties of UN through simulating diffusion in hypo-stoichiometric UN. This chapter builds on my findings in my previous chapter, and looks at how the fission gas atom xenon behaves in UN.

5.1 Introduction

Licensing a new accident tolerant fuel, such as UN, requires a detailed understanding of its macroscale properties and interactions with other materials in the reactor core under normal operating conditions as well as under accident conditions. As with oxide fuels, a major cause for concern is the release of fission gasses. Release of gas atoms into the plenum between the fuel and the clad may cause swelling, thereby exerting hoop stresses on the cladding, that can compromise its structural integrity, resulting in the release of radioactive material into the external coolant [541, 542].

Substantial effort has been expended to understand fission gas behaviour in UO_2.

However, there is significantly less equivalent data available for UN. Experimental studies have found that fission gas release inside a UN fuel pin varies with burn-up and temperature, and lowers the thermal conductivity of the fuel-cladding gap; additionally, the swelling of the fuel as a result of fission gas emission increases the pressure of the fuel [543–545]. Fission gas release, which increases proportionally with burn-up, occurs as a process whereby fission gas atoms are formed in fuel grains, and diffuse to grain boundaries where they arrange themselves in networks, whereafter they are released to the surfaces of the fuel [546, 547]. Further experimental studies on UN and similar systems have discussed the evolution of material properties during operation, including damage recovery in UN [548] and structural changes in nitrides such as dislocation loop and cavity formation [549–551]. The study by Xiu *et al.* [551] in particular found that $\frac{a}{2}\langle 110\rangle$ dislocation loops are formed as a result of irradiation. However, experimental research on UN systems, especially fission gas release research, remains relatively limited.

The gas contained in mixed uranium-plutonium nitride fuel rods has been found to be comprised of mainly three elements: helium, krypton, and xenon [115], much like the gas composition in UO_2 [87, 103, 552]. Once generated, these fission gas atoms are accommodated in point defects in the lattice. For UO_2, it has been shown the incorporation of fission gas atoms at Schottky defects is most energetically favourable [89, 553–556]. However, the availability of such trapsites depends on the stoichiometry of the fuel, with Andersson *et al.* predicting that the preferred mechanism for xenon solution changes from Xe_{UO_2} to Xe_{UO} and then Xe_U for UO_{2-x}, UO_2 and UO_{2+x} respectively [557]. In all cases, however, fission gas atoms are insoluble in the lattice and so there is a thermodynamic driving force for them to cluster together and form intra- and intergranular gas bubbles. In UO_2, these fission gas bubbles can form above a certain temperature threshold, where both burn-up and temperature influence fuel swelling [558]. This migration and clustering was found to originate from diffusion in different temperature regimes; Turnbull *et al.* describes the occupation and movement of xenon atoms on vacancy sites at high temperatures, whereas at lower temperatures, radiation-mediated diffusion dominates [559, 560]. Once these bubbles have formed it is essential to understand the key thermodynamic properties of the gasses contained within, particularly their pressure. Previous research shows that noble gas atoms can form solid inclusions in UO_2 dependent upon bubble size, pressure and temperature, and recent data suggests similar behaviour in UN [561]. Moreover, it has been found that small bubbles (ranging from $1 - 10$ nm in diameter) are immobile in a reactor under normal operation [562].

The work presented in this chapter utilises a mixture of MD and DFT to examine the behaviour of xenon in UN. DFT in particular has been used extensively to study point defects in UN; such defects can accommodate changes in stoichiometry as well as facilitate fission product migration through the fuel: Kotomin *et al.* [563] conducted one of the earliest DFT studies of point defects in UN, where it was found that the presence of V_{N} defects has little impact on the lattice parameter, whereas V_{U} defects have a larger defect volume. Furthermore, formation energies for Schottky and Frenkel pairs were found to be similar. Other DFT research into point defects has found that for hypo-stoichiometric and hyperstoichiometric UN, V_{N} and N_i dominate, respectively [564]. It should be noted, however, that in this previous work the chemical potentials were simultaneously set to $1/2\mathrm{N}_2$ gas for N and α-U for U, conditions which cannot exist at the same time. It has also been observed that the displacements of the nearest neighbour atoms of V_{U} defects are larger in magnitude than those for V_{N} [565]. DFT simulations have also been employed to consider incorporation of fission products in UN [566, 567] as well as their diffusivities [568, 569]. These works indicate that both xenon and krypton are preferentially accommodated in Schottky defects in UN, in a similar way to UO_2. However, thus far only incorporation of isolated fission gas atoms has been considered and there are no simulation studies of fission gas bubbles in UN. Therefore, this work will derive a new empirical potential model for xenon in UN and use this model to understand the properties of xenon bubbles in the fuel.

5.2 Methodology

As discussed previously, to enable the simulation of xenon bubbles in UN it is necessary to develop a new potential to represent the interactions between the gas atom and the crystal lattice. This will be done by fitting to incorporation energies for xenon in point defects in UN calculated using DFT. The defect processes studied here are denoted in Equations 5.1, 5.2, 5.3, and 5.4, representing the processes for xenon accommodation on uranium, nitrogen, Schottky and interstitial sites, respectively.

$$V_{\mathrm{U}} + \mathrm{Xe} \rightarrow \mathrm{Xe}_{\mathrm{U}} \tag{5.1}$$

$$V_{\mathrm{N}} + \mathrm{Xe} \rightarrow \mathrm{Xe}_{\mathrm{N}} \tag{5.2}$$

$$V_{\mathrm{UN}} + \mathrm{Xe} \rightarrow \mathrm{Xe}_{\mathrm{UN}} \tag{5.3}$$

$$\mathrm{Xe} \rightarrow \mathrm{Xe}_{i} \tag{5.4}$$

The Murphy Materials Modelling Group at Lancaster University undertook DFT analysis of xenon occupation in UN, and evaluated various incorporation energies, which can be seen in Table 5.1, where they are compared with the results of Claisse *et al.* [566], Kuganathan *et al.* [570], and Yang and Kaltsoyannis [89]. The research group also created a corresponding Brouwer diagram showing how xenon can be accommodated in UN, as shown in Figure 5.1 [540]. This Brouwer diagram shows the concentration of certain defects at various stoichiometries. It should be noted from this Brouwer diagram that there is a tendency for Xe_{U} to dominate at hyper-stoichiometry, and for Schottky xenon defects to dominate at hypo-stoichiometry; this compares well to Yang and Kaltsoyannis' results which show that Schottky defects in hypo-stoichiometric conditions and uranium vacancies in hyper-stoichiometric conditions are the most energetically favourable sites for xenon as well as krypton [89].

Defect	**DFT incorporation energy (eV)**			
	This work	Claisse*et al.*	Kuganathan*et al.*	Yang*et al.*
$\mathrm{Xe_U}$	3.82	3.74 (3.61)	3.54	4.70
$\mathrm{Xe_N}$	7.82	8.45 (7.90)	8.66	9.14
$\mathrm{Xe_{UN}}$	2.07	2.79 (2.64)	2.80	3.12
Xe_i	14.08	14.64 (13.18)	13.00	15.53

Table 5.1: Incorporation energies of xenon on various UN defect sites from DFT [540], compared to similar incorporation energies from Claisse *et al.* [566], as well as the DFT data from Kuganathan *et al.* [570] and values from Yang and Kaltsoyannis [89]. The corrected energies from Claisse *et al.* that include elastic interactions are denoted in the brackets.

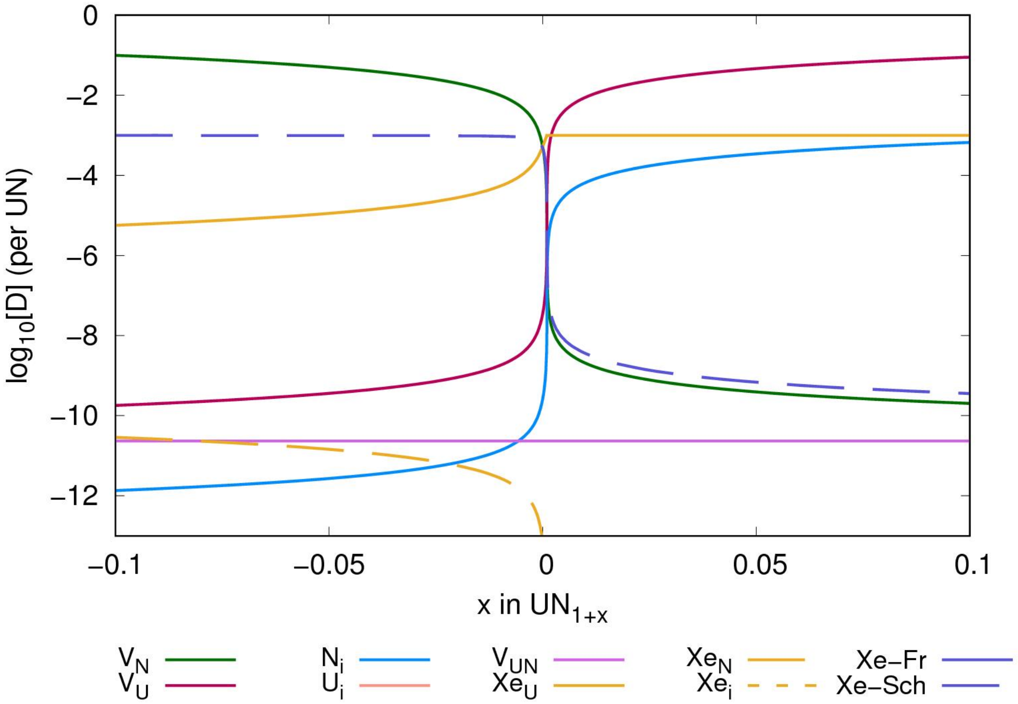


Figure 5.1: A Brouwer diagram showing the concentrations of various intrinsic and extrinsic xenon defects in UN. Defects that are too low in concentration to be discernible in the diagram have been omitted [540].

5.2.1 Molecular dynamics

Potential fitting and simulations of bubble formation were both performed with LAMMPS [239]. As before, an angular dependent potential developed by Tseplyaev and Starikov for UN was used. This potential originated from an embedded atom method potential produced by Mishin, Mehl, and Papaconstantopoulos [251, 252]. The potential model employed for Xe-Xe interactions was that of Tang-Toennies [260].

Simulation supercells were created using using Atomsk [242]. A UN supercell was made up of 15×15×15 repetitions of the unit cell (27×10^3 atoms) along the x, y, and z directions for the UN-Xe potential fitting. For the bubble simulations only, the system was scaled up to become a 100×100×100 supercell (8×10^6 atoms); this was done in order to accommodate bubbles of larger sizes. Energy minimisations were conducted using a conjugate gradient minimiser, specifically the Polak-Ribière form [571]. All system equilibrations were carried out under a Nosé-Hoover barostat (NPT conditions) with a pressure damping parameter of 1 ps, and Nosé-Hoover thermostats (NVT conditions) were used for xenon bubble insertions with a temperature damping parameter of 0.1 ps.

The timestep used for all simulations was 0.001 ps, and periodic boundary conditions were in effect for all simulations. Visualisation of the resulting simulations was conducted using OVITO [243].

Potential fitting

To enable the simulation of xenon in UN we fit a new potential for the Xe-N and Xe-U interactions using the Buckingham potential, as shown in Equation 2.35. New potential parameters were derived using the Potential Pro-Fit (*PPro-Fit*) program developed by Rushton [256, 572] and were fitted to reproduce the incorporation energies obtained from DFT, starting from the model of Cooper *et al.* [256–260] for UO_2.

Bubble simulations

For the simulation of bubbles in the UN lattice, a similar approach to that of Galvin *et al.* for xenon in UO_2 was adopted [573]. Stoichiometric voids were constructed by removing a sphere of equal amounts of uranium and nitrogen atoms from the centre of the supercell, as shown in Figure 5.2. These voids were formed with initial diameters of 5, 10, 15, and 20 unit cell parameters of UN, which corresponded to void radii of 1.2, 2.4, 3.6, and 4.8 nm. It can be assumed that voids exist in real UN, because voids are an inevitability when manufacturing materials; no material is 100% theoretical density. These simulation supercells were energy minimised and then equilibrated at both 300 K and 1200 K for time periods scaled with the size of the bubble in order to properly relax the surrounding lattice; no significant atomic movement was seen in longer void equilibrations, only vibrations of the atoms about their sites.

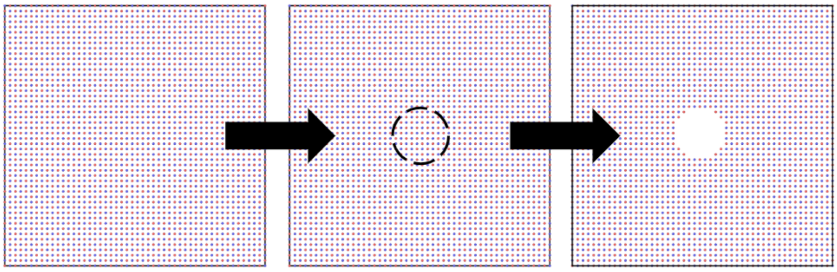


Figure 5.2: The creation of a central spherical void in the UN supercell. The dashed circle illustrates the boundary of the atom deletion, set by the desired void radius. The final void underwent xenon atom population.

The addition of xenon atoms was done gradually under NVT conditions, with a period of 25 ps in between each set of atom insertions to allow for equilibration. A constraint was applied to atom insertions to ensure that atoms were not placed too close together; no xenon atom could be inserted within 2.3 Å of existing atoms. This exclusion radius was defined such that xenon atoms were prevented from being inserted too close to each other such that high velocities, and therefore cascades, are averted. One atom insertion took place every 0.01 ps in order to simulate a quasistatic process. The length of time in which atom insertions occurred was scaled with an increase in void size to ensure proper aggregation of the bubble. Specific ratios of xenon atoms added to UN formula vacancies removed (Xe: V_{UN}) were explored from 0.1 to 1 in increments of 0.1, and from 1 to 1.25 in increments of 0.05. Hence, the amount of atoms inserted at each step corresponded to the ratio under investigation.

The pressures at different (Xe: V_{UN}) ratios were obtained from the calculation of the per-atom pressure tensor, P, over all xenon atoms from i to N, shown in Equation 5.5,

$$P = -\sum_{i}^{N} \left(\frac{\sigma_{xx}^{i} + \sigma_{yy}^{i} + \sigma_{zz}^{i}}{3V} \right) \tag{5.5}$$

where, σ_{xx}, σ_{yy}, and σ_{zz} are the normal stress components of the tensor, and V is the volume of the bubble, which was calculated using the Voronoi volume of the xenon atoms, obtained from their Voronoi tessellation after implementing the VORO++ package in LAMMPS [574].

The radial distribution function (RDF) is the probability of finding an atom at a distance r from a reference atom, often denoted as *g(r)*. In this study, the RDF was calculated every 0.1 ps, and 300 bins were used.

The formation energy of a void ($E^{\mathrm{f}}_{\mathrm{void}}$) and a bubble and a void ($E^{\mathrm{f}}_{\mathrm{bubble}}$) were calculated using Equations 5.6 and 5.7, respectively,

$$E^{\mathrm{f}}_{\mathrm{void}} = E_{\mathrm{void}} - \left(\frac{N_{\mathrm{void}}}{N_{\mathrm{perf}}} E_{\mathrm{perf}} \right) \tag{5.6}$$

$$E^{\mathrm{f}}_{\mathrm{bubble}} = E_{\mathrm{bubble}} - \left(\frac{N_{\mathrm{void}}}{N_{\mathrm{perf}}} E_{\mathrm{perf}} \right) \tag{5.7}$$

where, E_{void} is the energy of the voided system, E_{bubble} is the energy of the system containing the xenon bubble, N_{void} and N_{perf} are the numbers of atoms in the voided and perfect system, respectively, and E_{perf} is the energy of the perfect supercell. To obtain the bubble formation energy, the formation energy of the void was subtracted from that of the bubble and the void.

5.3 Results and discussion

5.3.1 Empirical potential fitting

The resulting Buckingham potential parameters for the new potential are presented in Table 5.2.

Parameter	**Xe-U**	**Xe-N**
A (eV)	3149.884	2864.077
ρ (eV)	0.326	0.298
C (eV $\cdot$ Å^{-6})	1.298	15.087

Table 5.2: The Buckingham potential parameters characterising a Xe-UN system.

The incorporation energies for xenon at point defects described by Equations 5.1, 5.2, 5.3, and 5.4 predicted using the new potential are compared to the DFT results in Table 5.3. The incorporation energies for the $\mathrm{Xe_U}$, $\mathrm{Xe_N}$, and $\mathrm{Xe_{UN}}$ processes are in excellent agreement with the DFT. However the incorporation energy at the interstitial site is considerably lower than the DFT value. This was a necessary trade-off during the potential fitting process as it was not possible to ensure the incorporation energy at the interstitial was accurate while maintaining the excellent agreement for the substitutional defects. It should be noted, however, that the incorporation energy at the interstitial site is still significantly higher than for other defects and so it is still unlikely to occur. Also included in Table 5.3 is a comparison to the results predicted by the recently developed potential of Kocevski *et al.* [575], although it should be noted that there exist some constraints in using interatomic potentials that are trained to a limited set of thermophysical properties to correctly represent phonon dispersions [576, 577]. There is excellent agreement between this work and the potential of Kocevski *et al.* for incorporation at the U and N sites. However, there is a significant discrepancy for incorporation into the Schottky and interstitial sites. The discrepancy predicted for the incorporation into the Schottky defect arises from Kocevski *et al.* predicting a higher energy for this defect in their DFT simulations. It also appears that Kocevski *et al.* had to compromise on the incorporation energy at an interstitial site as the discrepancy between the value from their potential and their DFT simulations is 1.5 eV.

Process	$E_{\textbf{inc}}^{DFT}$ **(eV)**	$E_{\textbf{inc}}^{Pot}$ **(eV)**	$E_{\textbf{inc}}^{Kocevski}$ **(eV)**
$\mathrm{Xe_U}$	3.815	3.696	3.96
$\mathrm{Xe_N}$	7.822	7.839	7.89
$\mathrm{Xe_{UN}}$	2.069	2.108	3.22
Xe_i	14.075	9.562	16.39

Table 5.3: A comparison of the incorporation energies obtained from DFT, and from the potential fit using the Buckingham parameters in Table 5.2, alongside the results obtained from the potential created by Kocevski *et al.* [575].

5.3.2 Bubbles

Given that the incorporation energies presented above are all positive it is expected that bubbles will form in the lattice, therefore, it is important to study the aggregation of xenon atoms. The formation energies for spherical voids and bubbles as a function of the number of UN formula units removed, $\mathrm{V_{UN}}$ at 300 K and 1200 K are presented in Figure 5.3. The results in Figure 5.3 were calculated using a Xe:$\mathrm{V_{UN}}$ ratio of 1.25:1 in the bubbles. The plot shows that the formation energies for the bubbles are greater than for the voids and that in both cases they decrease as the number of formula units removed is increased. A similar trend is observed in $\mathrm{UO_2}$ [573]. The formation energy for the bubble at the higher temperature decreases rapidly as UN is removed. This is likely due to the increased kinetic energy in the system allowing it to respond to increases in the size of the bubble. It should be noted that in $\mathrm{UO_2}$ it was necessary to manually introduce facetted voids. However, there was evidence of facetting occurring in our bubble simulations.

As the number of xenon atoms per unit of UN removed increases there is an initial dramatic increase in the pressure of the gas in the void. This is shown in Figure 5.4. However, at both temperatures the increase in pressure levels off. This occurs at a lower (Xe: V_{UN}) ratio at 1200 K and at a lower final pressure. The reason for this is that the lattice responds to the increase in pressure in the bubble by loop punching to relieve this pressure and that this dynamic process is more likely to

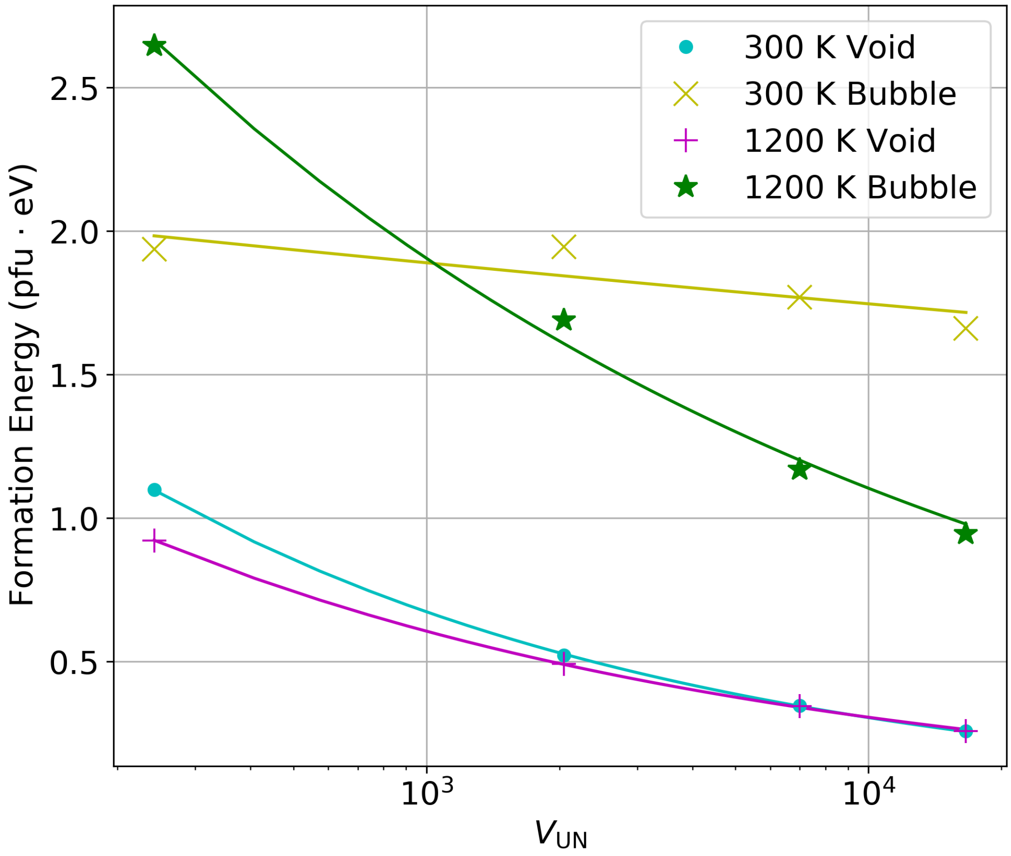


Figure 5.3: A plot of formation energies for spherical voids and bubbles at 300 K and 1200 K. The x-axis has been bound to a $\log_{10}$ scale, and a power relation was used for fitting. Online version in colour.

occur at the higher temperature.

As the atoms accumulate in the void, the arrangement of the xenon atoms changes. This is illustrated by the RDF plots shown in Figure 5.5 for both temperatures. At low (Xe: V_{UN}) ratios, the RDF indicates that there is no structure in the Xe. However, as the (Xe: V_{UN}) ratio increases there is clear evidence of the formation of identifiable peaks that correspond to the formation of solid xenon in the UN. In Figure 5.5, the RDF plot for the bubble at 300 K displays distinctive *fcc* behaviour, and the RDF plot for the bubble at 1200 K exhibits *bcc* behaviour, as seen from typical RDF plots for these structures [578, 579]. Therefore, there is evidence of a phase transition in the bubble between the temperatures of 300 K and 1200 K.

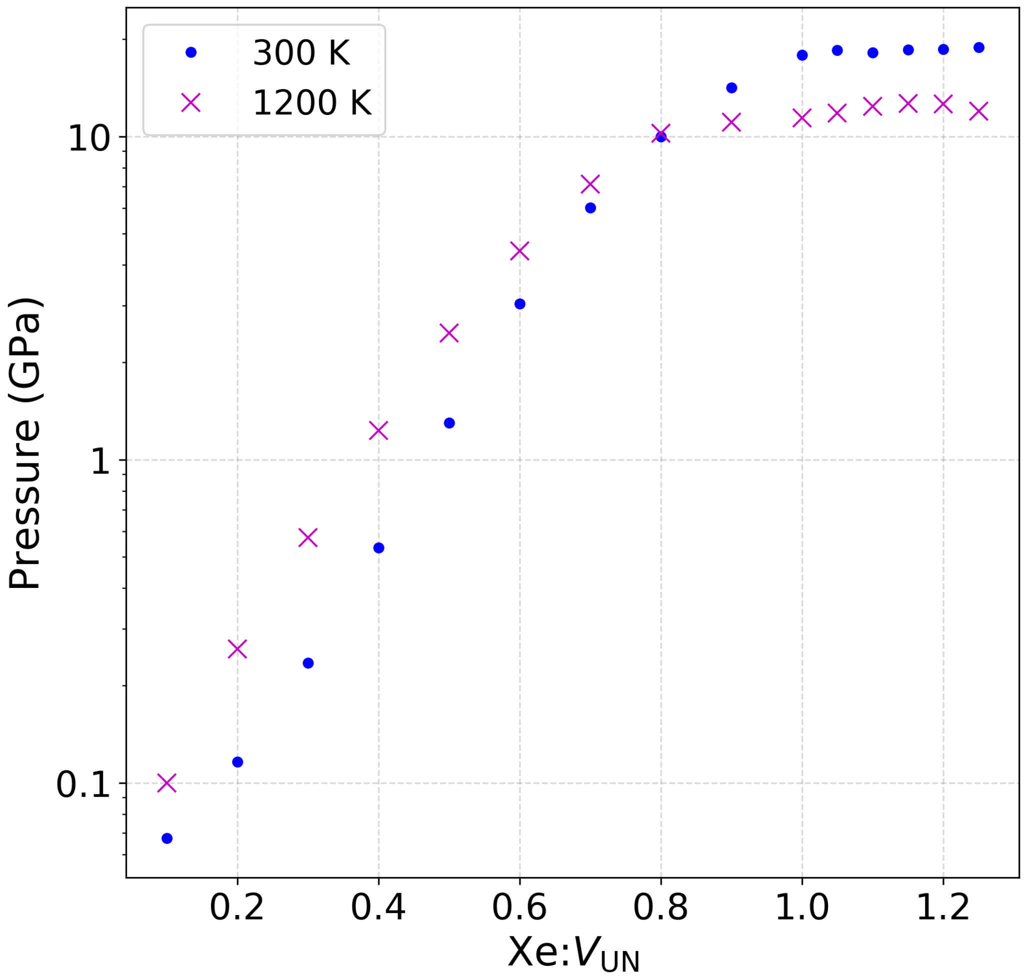


Figure 5.4: A $\log_{10}$ plot of pressure for a bubble of radius 4.8 nm, varying with (Xe: V_{UN}) at 300 K and 1200 K.

An image of a fully-formed xenon bubble is shown in Figure 5.6, where the Common Neighbor Analysis in OVITO [580] has been used to identify the different crystal structures present in the bubble. It is clear that the xenon has become more ordered indicating solidification at higher pressures, corroborating the observations of Degueldre *et al.* [561]. Specifically, both *fcc* and *hcp* crystal structures are predicted to occur due to the growth of the xenon bubble being constrained by the UN lattice.

As discussed above, at the higher (Xe: V_{UN}) ratios, the bubbles attempt to relieve the pressure by loop punching. The formation of dislocation loops is illustrated in Figure 5.7, where the dislocations were identified using the dislocation analysis

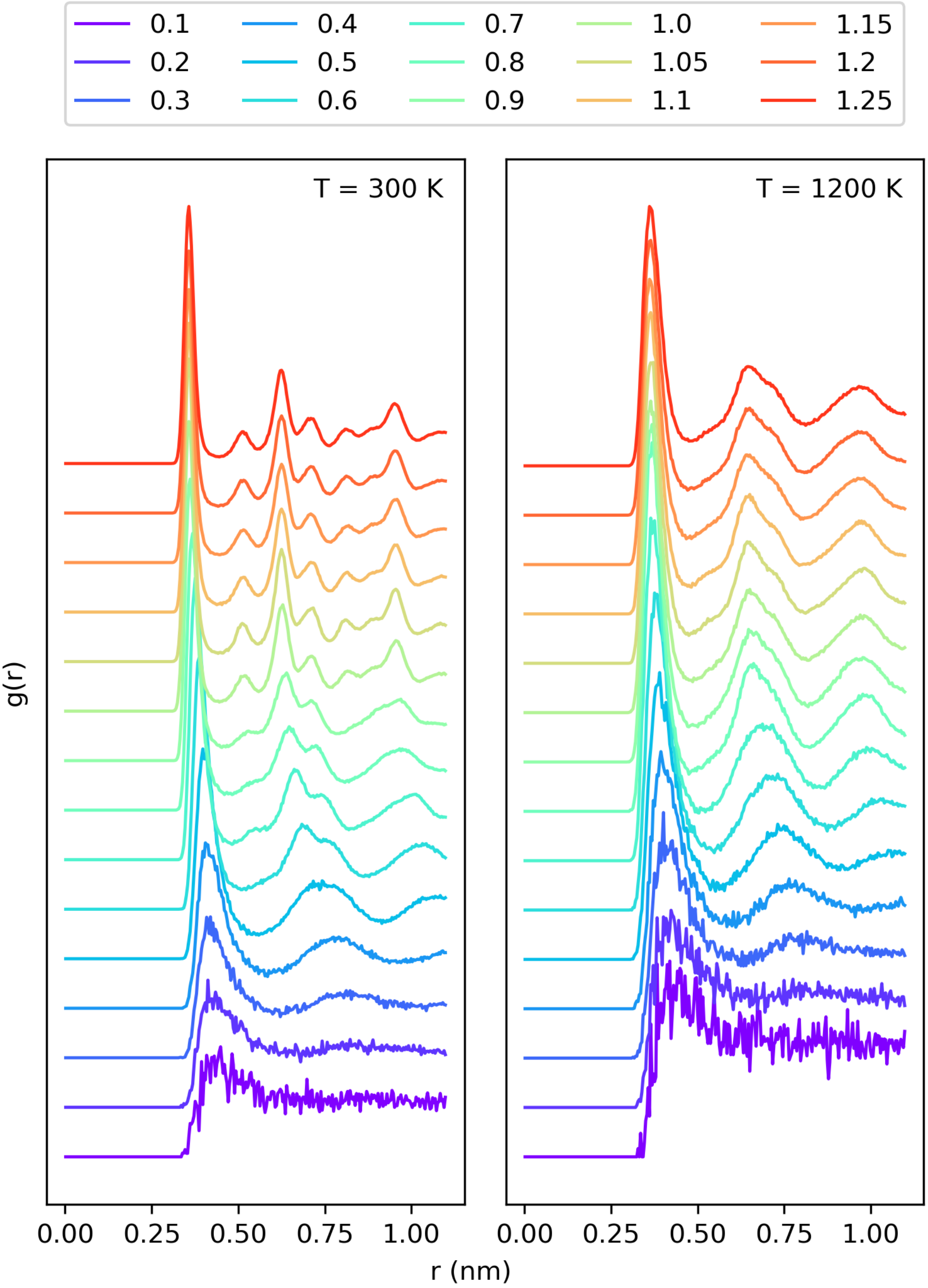


Figure 5.5: The RDF plots for xenon in a bubble of radius 4.8 nm at 300 K (left) and 1200 K (right). The y-axis is an arbitrary representation of the RDF, numerically shown as g(r). The values in the legend denote the Xe:V_{UN} ratios. Online version in colour.

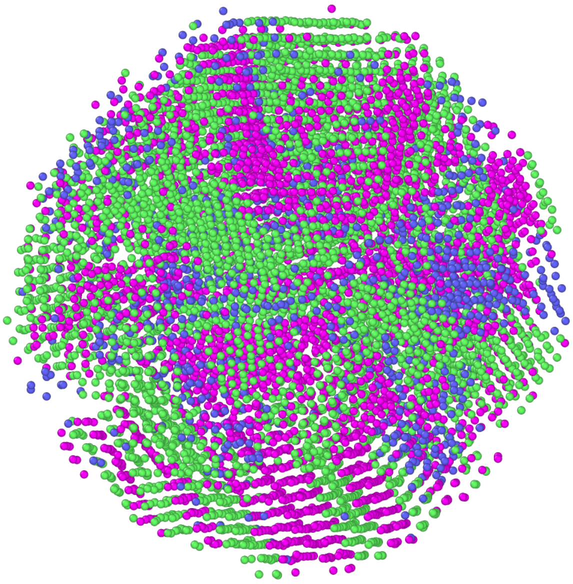


Figure 5.6: A xenon bubble with a diameter of 9.6 nm at 300 K, with regions of crystalline structure identified. Here, *fcc*, *hcp*, and *bcc* regions are represented using green, magenta, and blue, respectively. Online version in colour.

tool in OVITO [243, 581].

Loop punching has been theorised to be a behaviour that relieves pressure in crystalline materials [582, 583], enabling further bubble growth [584]. Loop punching has been observed previously in *fcc* materials such as copper implanted with helium [585] and hydrogen [586]. In tungsten, advanced loop punching from helium bubble growth was computationally observed in the form of dislocation nets from the interaction of dislocation loops [587]. In UO_2, loop dislocations have been observed in experimental TEM studies [588, 589], and classical MD simulations have revealed that dislocation loops arise from the nucleation of interstitial defect clusters [590, 591]. Here in UN, loop punching was particularly prominent in the largest bubbles as illustrated in Figure 5.7. During the simulation of this bubble at 1200 K, line dislocations materialised at pressures of 10.2 GPa and above. At pressures above this, the UN lattice is deformed to alleviate pressure to ensure that no xenon is re-solved into the lattice. These results could also suggest that loop punching in smaller bubbles might take place at even greater bubble pressures. Interestingly, Figure 5.7 shows that the loops punched out are consistently of a similar size to the bubble

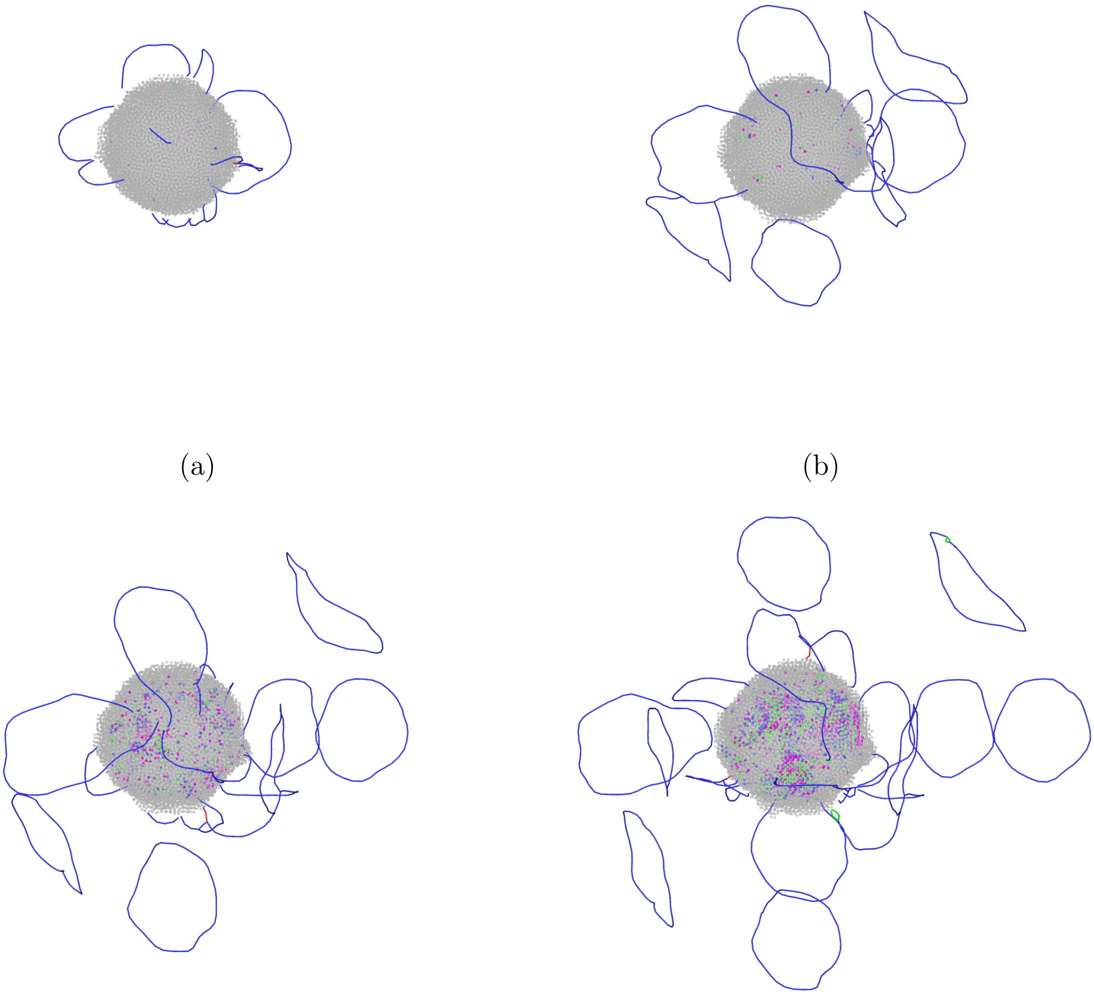

(a) (b) (c) (d)

Figure 5.7: The evolution and the loop punching of dislocations emanating from a 4.8 nm radius bubble at 1200 K. The blue lines represent the dislocation lines, and specifically denote Burgers vectors of $\frac{1}{2}\langle 110\rangle$. The line dislocations shown here belong to the U lattice only; corresponding dislocations were observed for the N sublattice. The elapsed time between the first capture of line dislocations in Figure 5.7a and the final capture showing significant loop punching in Figure 5.7d was 1.45 ns. The packing structures that OVITO identified as 'Other' are white and have been made 75% translucent. Online version in colour.

itself. The type of dislocation loops shown in Figure 5.7, $\frac{1}{2}\langle 110\rangle$ are also observed in UN when it is irradiated [551]. Loop punching is an important behaviour to study due to its effect on fuel creep during operation, and given the various complexities of experimentally validating loop behaviour in UN, such as mechanism ambiguity [550], there is scope for more research to take place in this area, both experimentally and theoretically, to reconcile the simulation results published in this study. In doing so, the findings of this study, with its own limitations, will be made more robust.

5.4 Summary

Classical MD methods have been used to explore the behaviour of xenon atoms in uranium mononitride. From previous DFT research, it has been shown that the most favourable site for accommodation of xenon depends on the stoichiometry of the underlying UN. For hypo-stoichiometric UN the $\mathrm{Xe}_{\mathbf{UN}}$ defect is predicted to dominate. However, due to the lack of availability of nitrogen vacancies, the $\mathrm{Xe}_{\mathbf{U}}$ defect is most favoured under hyperstoichiometric conditions. Under all conditions the Xe_i defect is expected to have a very low concentration owing to the relative size of the xenon atom and the space available at the interstitial site.

A new Xe-UN Buckingham potential was developed by fitting to the incorporation energies determined from DFT. The new potential is able to reproduce the predicted ordering of the incorporation energies and gives very accurate incorporation energies for the Xe_{U}, Xe_{N} and $\mathrm{Xe}_{\mathrm{UN}}$ defect processes.

The accumulation of xenon atoms into bubbles was studied in spherical voids, and the bubble formation energy was found to decrease with larger sized bubbles. It was also found that bubble pressures increased with higher ($\mathrm{Xe}\colon V_{\mathrm{UN}}$) under the defined limiting distance for insertion. Generally, at low temperatures, the large majority of the bubble structure belongs to an *fcc* arrangement with stacking faults due to the constraints imposed by the UN lattice. A phase transition is observed to occur when the temperature increases, and at higher temperatures such as 1200 K, the bubble exhibits a *bcc* structure. The loop punching of dislocations was found to be significant for bubbles with a radius of 4.8 nm at high temperatures of 1200 K, at pressures of 10.2 GPa and above. These results suggest that UN prefers to undergo significant microstructural rearrangement rather than have xenon atoms resolved back into the lattice.

The results in this chapter indicate that UN is able to release stress surrounding fission gas bubbles through the formation of the dislocations by loop punching. This implies that the creep rate in UN may be increased relative to UO_2. However, the much-reduced thermal gradient due to the high thermal conductivity of UN may compensate for this. Therefore, the further modelling of complex phenomena in UN, such as creep, requires further investigation.

In this chapter, I explored the behaviour of xenon bubbles in UN, and discovered the lattice distortions that take place with high pressure bubbles. This chapter, along with Chapters 3 and 4, help to develop the creative-critical future in the next chapter, as can be seen in Figure 5.8.

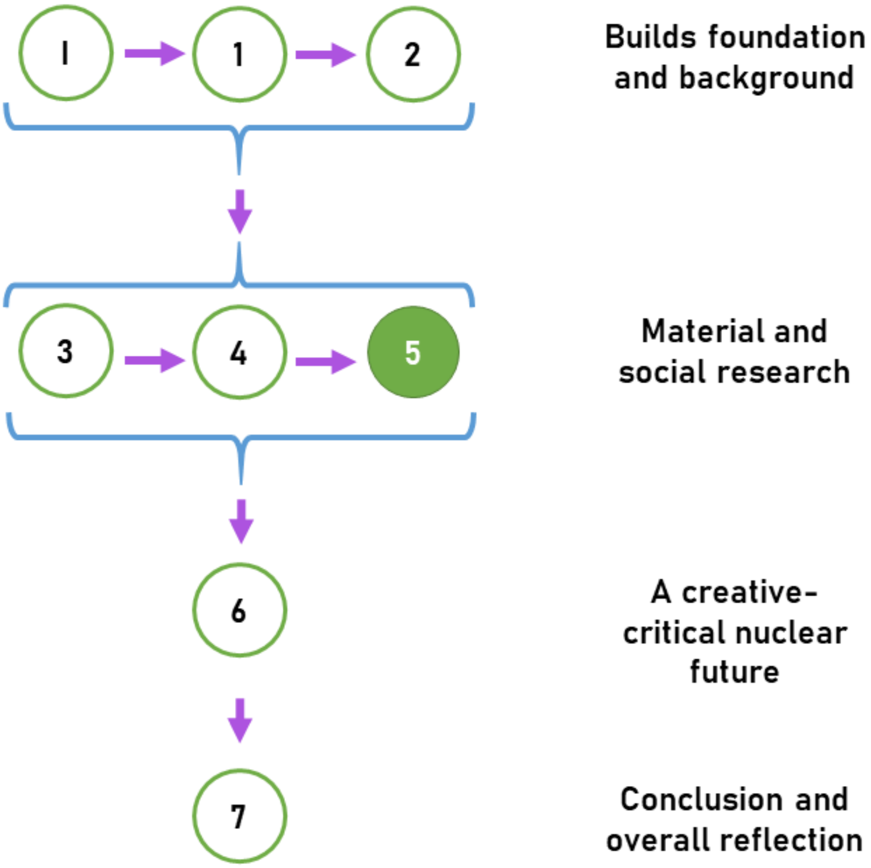


Figure 5.8: A map of the thesis structure. The chapter that we are in now ('5') has explored the behaviour of xenon atoms in the UN lattice.

Chapter 6

A nuclear future

In the previous chapter, I used molecular dynamics simulations to explore the behaviour of xenon atoms in the UN lattice in order to look at how the materials respond to certain conditions. In this chapter, I will take my knowledge that has been built up in the previous chapters to develop a creative-critical future around a fictional accident scenario.

6.1 Introduction

In this chapter, I present artefacts that individually provide glimpses into a future world involving nuclear power and UN. However, when combined, these artefacts tell a story that incorporates the emotive social aspects of nuclear power that are often sidestepped in nuclear materials developments, and draws upon the tenets of immersion and estrangement to facilitate world-building. In addition to the engagement that immersion and estrangement facilitate for futures thinking, a creative methodology has been used in this chapter to explore complexity, depth, and interpretability in material and social issues. Essentially, it not just that the story drives the human aspects of issues—stories allow us to go deeper and to different places, and force us to reflect on our own interpretations. As my futures work emerges from robust qualitative research, the themes found in Chapter 3 are incorporated here, and are explored further in the artefacts commentary.

The core concept of this chapter lies in exemplifying how exploring the social futures of materials, in tandem with the material futures of societies, could practically work through developing and fusing existing and imagined narratives. Chapters 4 and 5 build on the nuclear discourse discussed in Chapter 3 as technological developments that arise from living with nuclear power, and Chapter 6 uses the discursive elements of this thesis to build an imagined narrative around nuclear futures. Following from this, ATFs are necessary to thinking about nuclear futures, as it is an area of research where the materials being explored have the potential to be implemented in the future. Additionally, I have posited ATFs as an example of a future technology, which is certainly necessary when considering nuclear futures, as it is the developments in technology that can propel advances towards our futures. Discourses by media, government, and opposition groups are also important in shaping these futures, as collective voices that have influence can shape the narrative and understanding of individuals and groups.

To fuse existing and imagined narratives, the constructed creative-critical future seeks to repurpose and combine our current understandings of nuclear power through an interdisciplinary lens. By this, I mean that I am demonstrating through this chapter the power of an interdisciplinary approach to thinking about materials and futures. I am showing how the scientific understandings of the future of ATFs cannot be considered in a vacuum: they intersect with social, cultural, ethical concerns, which through the vehicle of a creative-critical future, are brought into clear conversation with the scientific knowledge. The reader is encouraged to view the artefacts in the order presented here, followed by the accompanying commentary. To aid in cross-referencing the artefacts in the commentary, a glossary has been included.

6.2 Artefacts from a nuclear future

Glossary of artefacts

2049: A controversial arrival

A1: The Alcoves newspaper article announcing the usage of UN

A2: Poem – “The Party”, WRENL/2049/41

A3: Alexis’ Canopy – local Wrenlock network discussing the newspaper

A4: Sebin’s Canopy – private messages with Alexis

A5: BBN1 live interview with Beth Clemmons

A6: Sebin’s Canopy – private group chat with her school friends

A7: Sebin’s diary entry – WRENL/2049/101

2050: Nuclear tempest

A8: Alexis’ Canopy – local Wrenlock network discussing the storm

A9: Sebin’s diary entry – WRENL/2050/34

A10: BBN1 live interview during the storm

A11: NRB’s incident summary file for Wrenlock 1

A12: Sebin’s diary entry – WRENL/2050/81

A13: Poem – “What we all leave behind”, WRENL/2050/124

2055: Reflections from afar

A14: Sebin’s Canopy – private messages with Alexis

A15: Sebin’s diary entry – WRENL/2055/23

A16: The Alcoves newspaper article reflecting on the event

A17: DEIC policy recommendations

A18: Poem – “Stopping”, WRENL/2055/34

2049

A controversial arrival

Tim Olton pays £350,000 fine for illegal skydiving stunt

Groundhog Day in hell—scorching temperatures and fields set ablaze in latest heatwave

Lancashire twins found alive in double murder plot

Friday
28th May
2049

Bringing the news to you since 1968

The Alcoves £3.50

Large-scale production of new nuclear fuel to begin in the UK

Mugi Mozalk

The large-scale production of a new fuel for nuclear reactors is expected to start in late 2049.

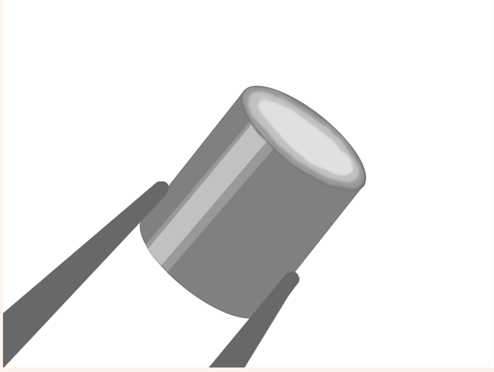
The Nuclear Regulatory Body (NRB) approved the licensing of uranium nitride in April 2048, allowing the fuel manufacturer Breamfin Fuels Ltd to commence production of uranium nitride at its Crowmill site, near the recently-completed reactor, Wrenlock 1.

Uranium nitride (UN) has its roots stretching back to the mid-1900s, where it was initially developed as a fuel for space reactors. After the nuclear accident at Fukushima, industry focus pivoted to alternative fuel technologies, ramping up research and design into UN.

The new fuel is expected to be used in Gen IV nuclear reactors, which use advanced technologies to economically and efficiently produce electricity, according to the Global Nuclear Organisation (GNO).

Pol Tebris, head of the GNO, says that “fuels like UN will help us with our energy crisis.

“These amazing fuels will be of huge benefit in our damaged climate”.



Breamfin Fuels Ltd claims they will manufacture “hundreds and thousands of UN fuel pellets a day”. Photograph: Siggy Lin/The Alcoves

However, critics say that the new fuel is unnecessary. A Wrenlock resident said that “what the people of Wrenlock need is working public transport, housing security and social support. No-one in Wrenlock can use UN in a meaningful way. This is a really disappointing development”.

Wrenlock has been known in the past decade for skyrocketing unemployment rates and social and economic deprivation, and was recently voted “Worst UK town” in 2048 by GreatHomecare magazine readers.

The north-western coastal town, which has a population of nearly 7,000, was once famed for its booming animal husbandry industry prior to the UK’s move away from meat products in the last decade.

The controversial unveiling of plans for the Wrenlock 1 reactor led some in the Wrenlock community to protest against the expansion of nuclear power in the area, calling for an end to nuclear expansion in the area.

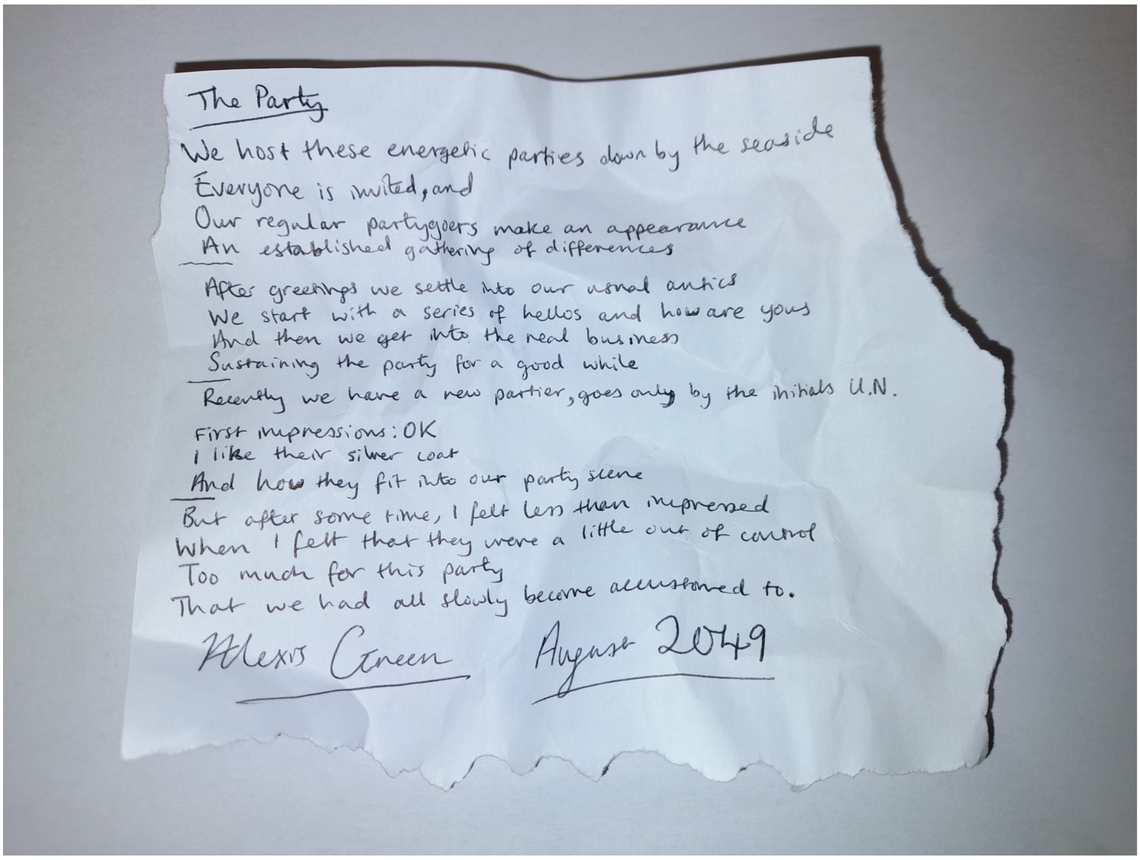
A spokesperson for Breamfin Fuels said that “there are many benefits of using UN—it contains more uranium within the material, so the fuel will need to be replaced much less often. It also enhances reactor safety”.

After testing, the first batch of UN fuel will be initially used in the Wrenlock 1 reactor, which began operations in March.

A1

WRENL/2049/41
Poem found in an abandoned residence in the wake of the Wrenlock Wreck

From Wrenlock Community Archive



The Party

We host these energetic parties down by the seaside
Everyone is invited, and
Our regular partygoers make an appearance
An established gathering of differences

After greetings we settle into our usual antics
We start with a series of hellos and how are yous
And then we get into the real business
Sustaining the party for a good while

Recently we have a new partier, goes only by the initials U.N.

First impressions: OK
I like their silver coat
And how they fit into our party scene

But after some time, I felt less than impressed
When I felt that they were a little out of control
Too much for this party
That we had all slowly become accustomed to.

Alexis Green
August 2049

TRANSCRIPTION

The Party

We host these energetic parties down by the seaside

Everyone is invited, and

Our regular partygoers make an appearance

An established gathering of differences

After greetings we settle into our usual antics

We start with a series of hellos and how are yous

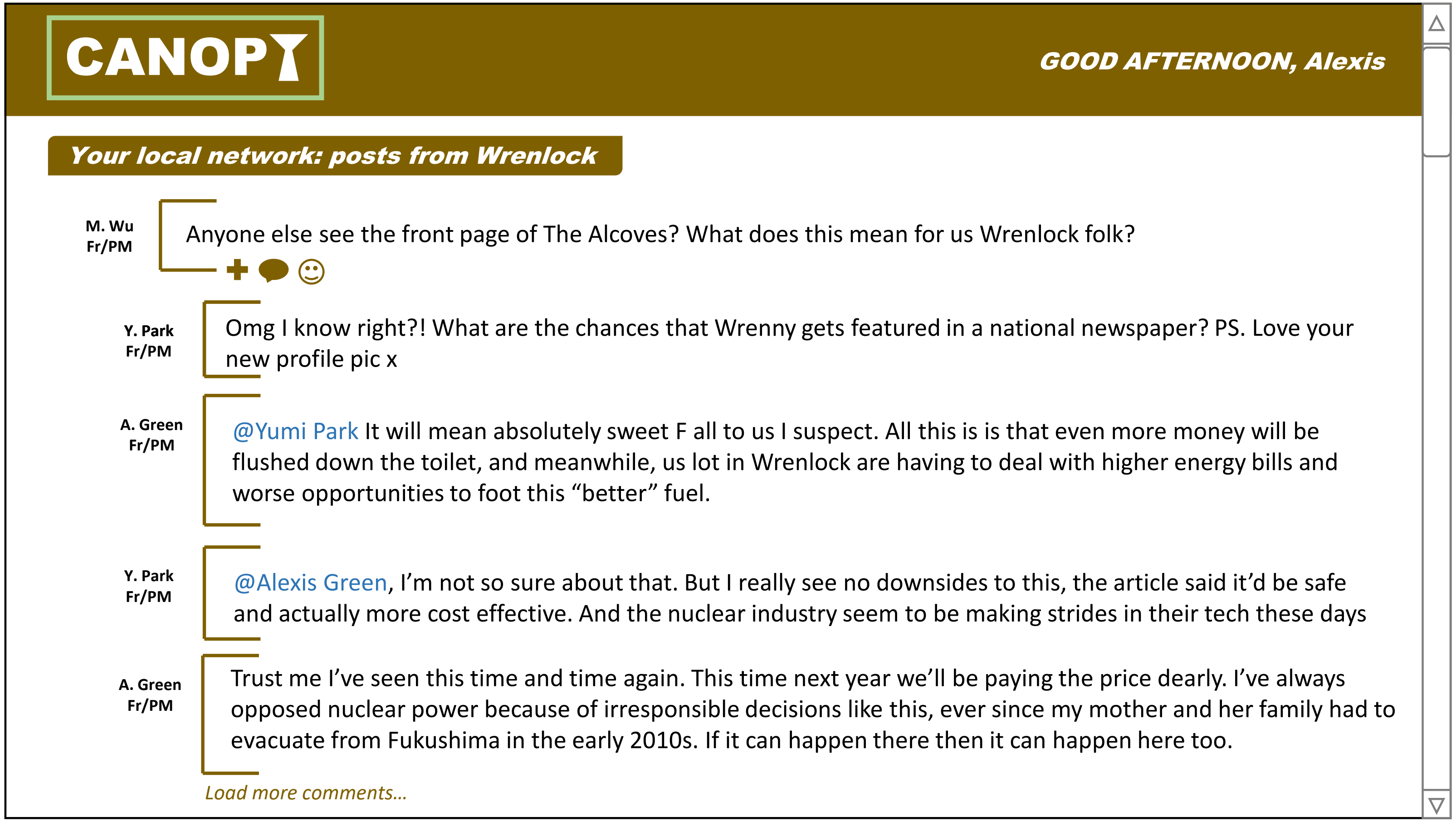
And then we get into the real business
Of sustaining the party for a good while

Recently we have a new partier, goes only by the initials U.N.
First impressions: OK
And I like their silver coat
And how they fit into our party scene

But after some time, I felt less than impressed
When I felt that they were a little out-of-control
Too much for this party
That we had slowly become accustomed to.

Alexis Green *August 2049*

A2



M. Wu
Fr/PM
Anyone else see the front page of The Alcoves? What does this mean for us Wrenlock folk?

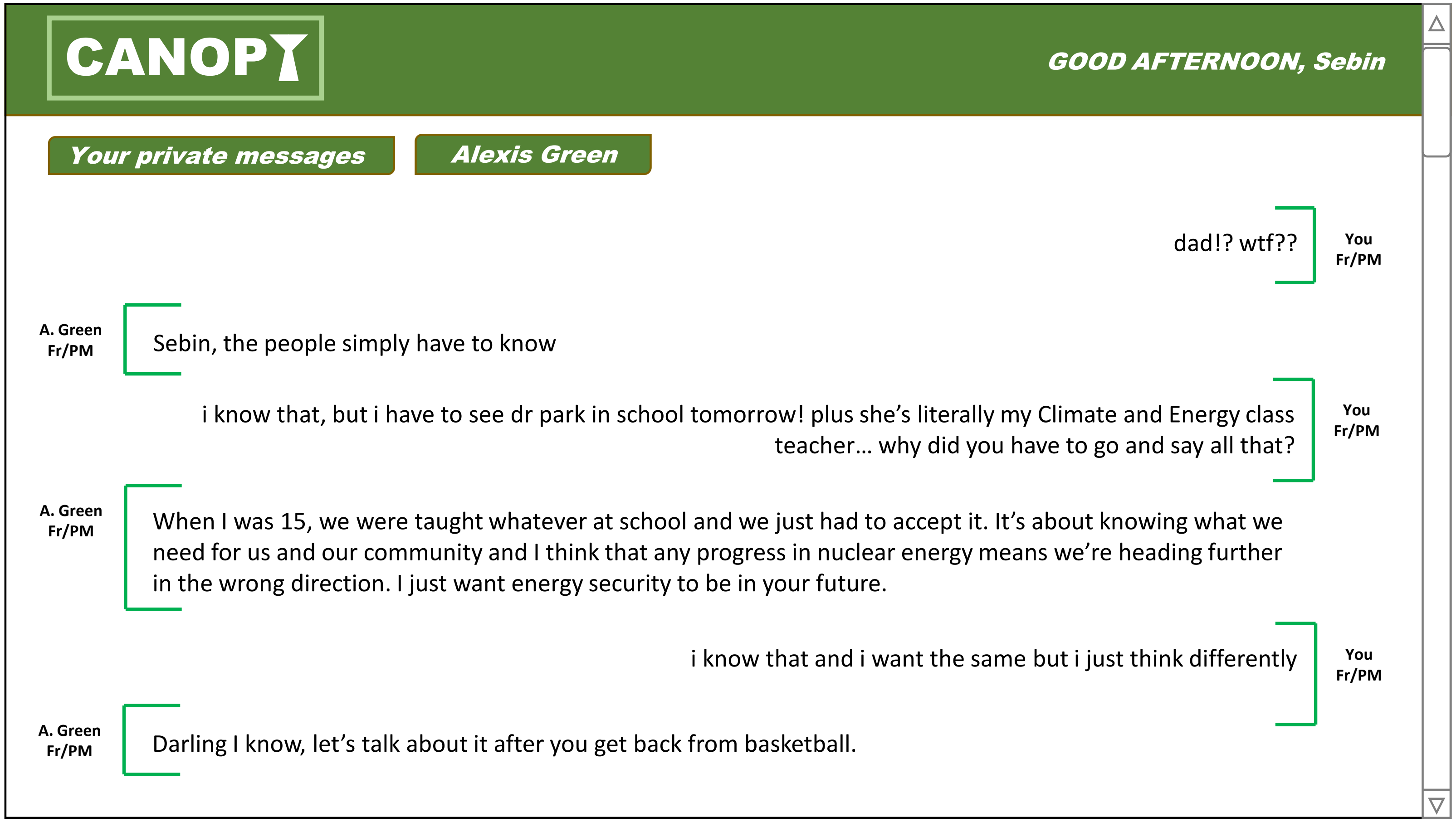
Y. Park
Fr/PM
Omg I know right?! What are the chances that Wrenny gets featured in a national newspaper? PS. Love your new profile pic x

A. Green
Fr/PM
@Yumi Park It will mean absolutely sweet F all to us I suspect. All this is is that even more money will be flushed down the toilet, and meanwhile, us lot in Wrenlock are having to deal with higher energy bills and worse opportunities to foot this “better” fuel.

Y. Park
Fr/PM
@Alexis Green, I’m not so sure about that. But I really see no downsides to this, the article said it’d be safe and actually more cost effective. And the nuclear industry seem to be making strides in their tech these days

A. Green
Fr/PM
Trust me I’ve seen this time and time again. This time next year we’ll be paying the price dearly. I’ve always opposed nuclear power because of irresponsible decisions like this, ever since my mother and her family had to evacuate from Fukushima in the early 2010s. If it can happen there then it can happen here too.

A3



You Fr/PM: dad!? wtf??

A. Green Fr/PM: Sebin, the people simply have to know

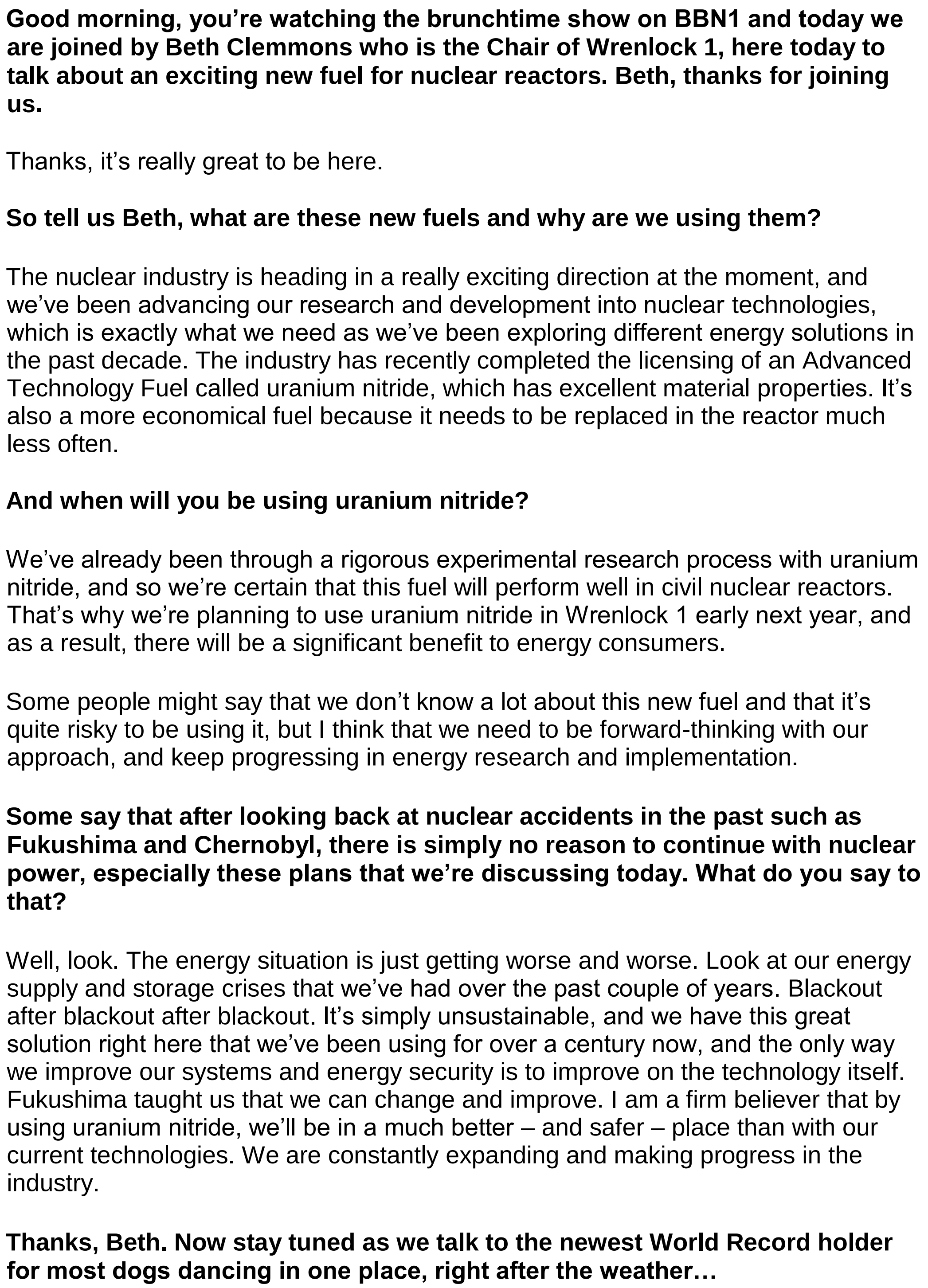
You Fr/PM: i know that, but i have to see dr park in school tomorrow! plus she's literally my Climate and Energy class teacher... why did you have to go and say all that?

A. Green Fr/PM: When I was 15, we were taught whatever at school and we just had to accept it. It's about knowing what we need for us and our community and I think that any progress in nuclear energy means we're heading further in the wrong direction. I just want energy security to be in your future.

You Fr/PM: i know that and i want the same but i just think differently

A. Green Fr/PM: Darling I know, let's talk about it after you get back from basketball.

A4



Good morning, you're watching the brunchtime show on BBN1 and today we are joined by Beth Clemmons who is the Chair of Wrenlock 1, here today to talk about an exciting new fuel for nuclear reactors. Beth, thanks for joining us.

Thanks, it's really great to be here.

So tell us Beth, what are these new fuels and why are we using them?

The nuclear industry is heading in a really exciting direction at the moment, and we've been advancing our research and development into nuclear technologies, which is exactly what we need as we've been exploring different energy solutions in the past decade. The industry has recently completed the licensing of an Advanced Technology Fuel called uranium nitride, which has excellent material properties. It's also a more economical fuel because it needs to be replaced in the reactor much less often.

And when will you be using uranium nitride?

We've already been through a rigorous experimental research process with uranium nitride, and so we're certain that this fuel will perform well in civil nuclear reactors. That's why we're planning to use uranium nitride in Wrenlock 1 early next year, and as a result, there will be a significant benefit to energy consumers.

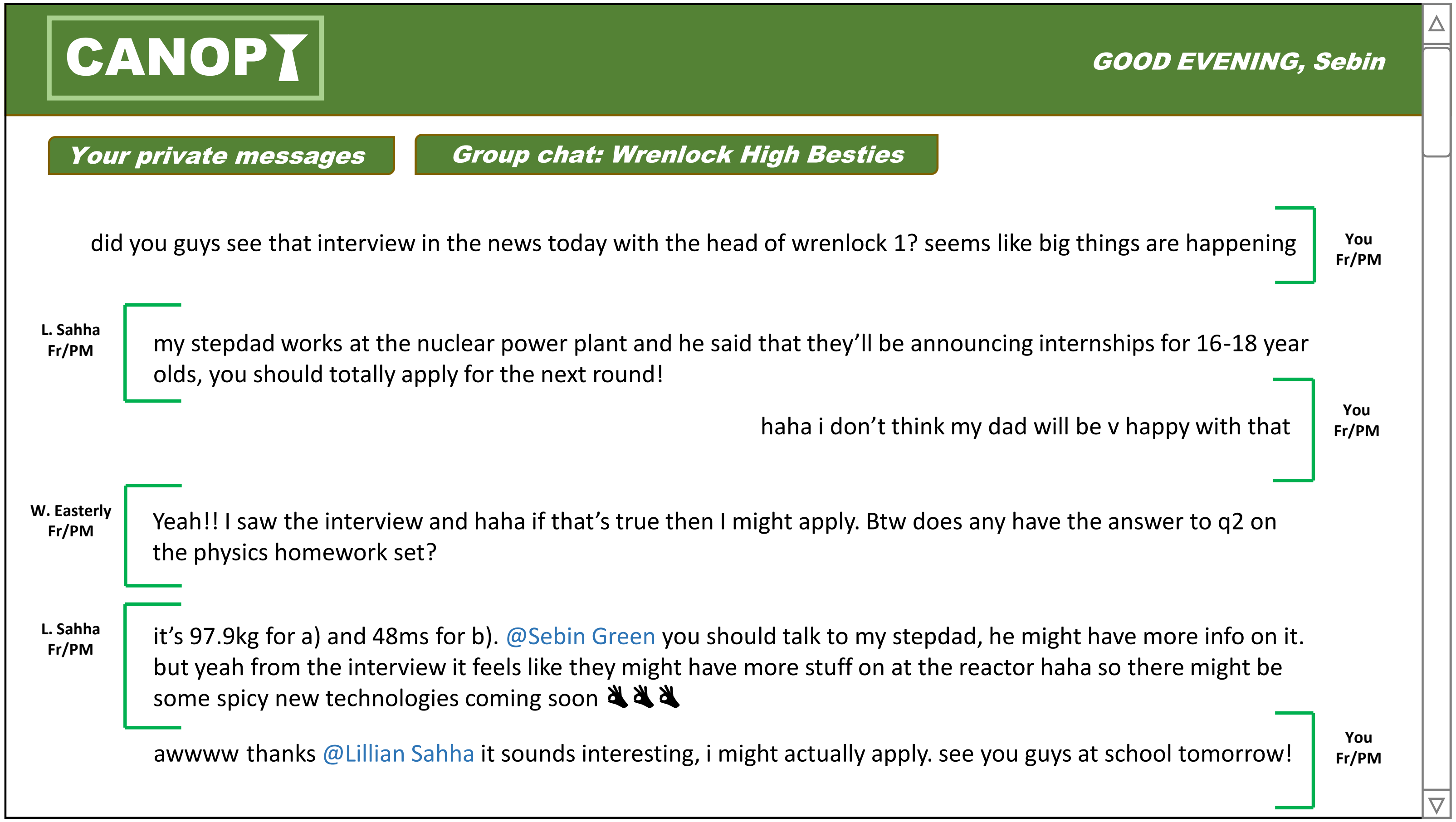
Some people might say that we don't know a lot about this new fuel and that it's quite risky to be using it, but I think that we need to be forward-thinking with our approach, and keep progressing in energy research and implementation.

Some say that after looking back at nuclear accidents in the past such as Fukushima and Chernobyl, there is simply no reason to continue with nuclear power, especially these plans that we're discussing today. What do you say to that?

Well, look. The energy situation is just getting worse and worse. Look at our energy supply and storage crises that we've had over the past couple of years. Blackout after blackout after blackout. It's simply unsustainable, and we have this great solution right here that we've been using for over a century now, and the only way we improve our systems and energy security is to improve on the technology itself. Fukushima taught us that we can change and improve. I am a firm believer that by using uranium nitride, we'll be in a much better – and safer – place than with our current technologies. We are constantly expanding and making progress in the industry.

Thanks, Beth. Now stay tuned as we talk to the newest World Record holder for most dogs dancing in one place, right after the weather…

A5



You Fr/PM: did you guys see that interview in the news today with the head of wrenlock 1? seems like big things are happening

L. Sahha Fr/PM: my stepdad works at the nuclear power plant and he said that they'll be announcing internships for 16-18 year olds, you should totally apply for the next round!

You Fr/PM: haha i don't think my dad will be v happy with that

W. Easterly Fr/PM: Yeah!! I saw the interview and haha if that's true then I might apply. Btw does any have the answer to q2 on the physics homework set?

L. Sahha Fr/PM: it's 97.9kg for a) and 48ms for b). @Sebin Green you should talk to my stepdad, he might have more info on it. but yeah from the interview it feels like they might have more stuff on at the reactor haha so there might be some spicy new technologies coming soon 👌👌👌

You Fr/PM: awwww thanks @Lillian Sahha it sounds interesting, i might actually apply. see you guys at school tomorrow!

A6

WRENL/2049/101
Diary entry donated and transcribed by Sebin Green, Wrenlock ex-resident

From "Exploring the Wrenlock Wreck" at NorthWest Museums

I just couldn't look Dr Park in the eye today as I was handing in my Climate and Energy homework. For some reason my dad had to go and make everything awkward on Canopy, and now I'm having to try and pretend like nothing happened at school, as if the whole world couldn't see his messages last night. What's worse is that after basketball he sat me down for a "discussion" where he was basically trying to dismiss everything Dr Park was saying... I just wanted a hole in the ground to swallow me up.

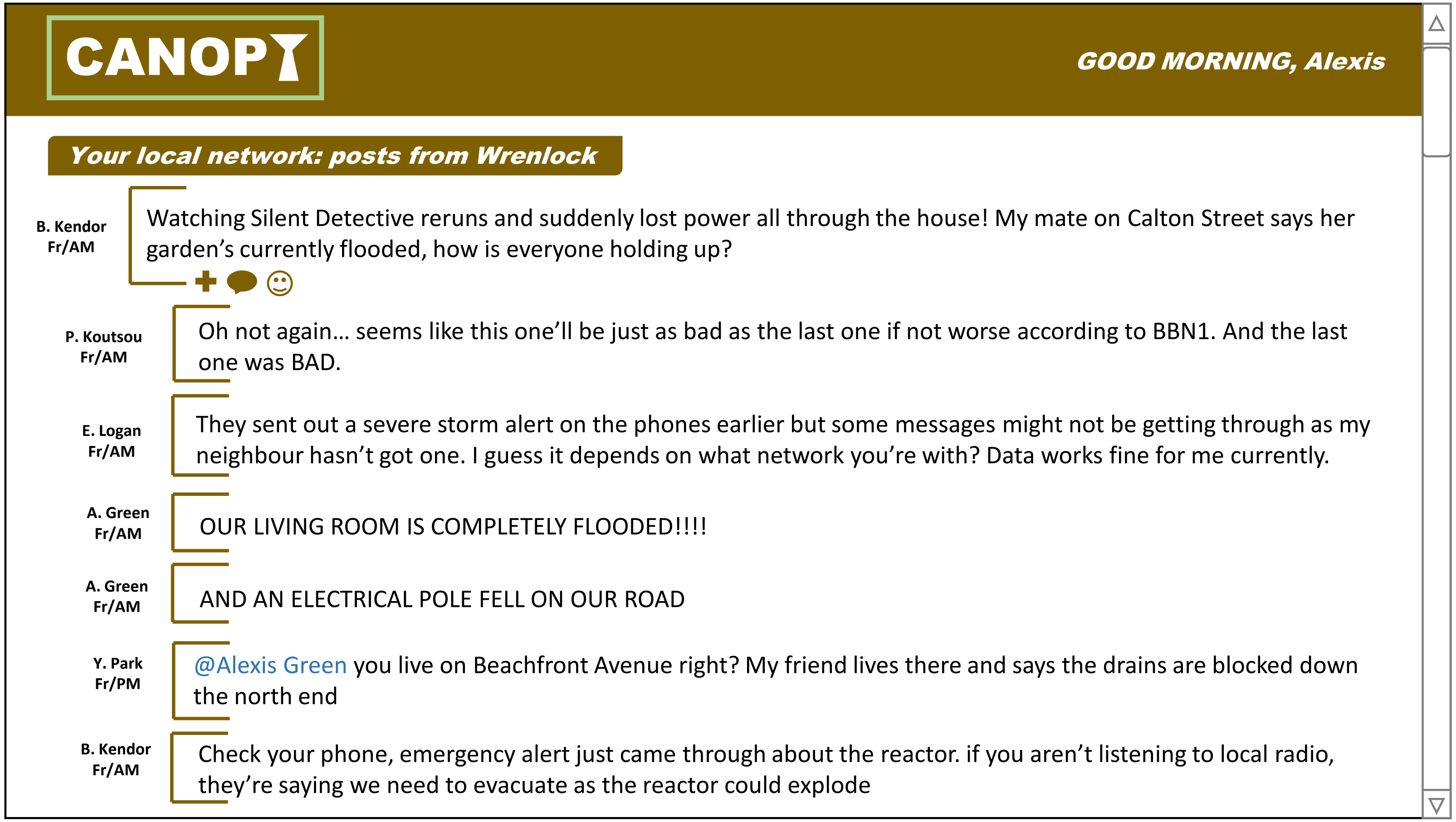
Dr Park got us to watch HBO's Chernobyl during class, it's this really intense drama series made in 2019 that basically shows what happened during Chernobyl back in the 1980s. It's terrifying watching people succumb to radiation sickness and watching it all unfold. I asked dad if he's seen it and he says that it should be a lesson for me...

I talked to Lillian's stepdad today and he was telling me about what actually goes on at a nuclear power plant. He's actually met Beth Clemmons, the head of Wrenlock 1, who was interviewed on live TV today, and said that Wrenlock 1 will actually be doing internships. I want to go for it. It'll be a difficult conversation with my dad but I hope he accepts that I really want to do this—it's sort of like an escape from Wrenlock and real life, where nothing exciting really happens anyway and nobody is there to help.

A7

2050

Nuclear tempest



Your local network: posts from Wrenlock

B. Kendor
Fr/AM
Watching Silent Detective reruns and suddenly lost power all through the house! My mate on Calton Street says her garden's currently flooded, how is everyone holding up?

P. Koutsou
Fr/AM
Oh not again… seems like this one'll be just as bad as the last one if not worse according to BBN1. And the last one was BAD.

E. Logan
Fr/AM
They sent out a severe storm alert on the phones earlier but some messages might not be getting through as my neighbour hasn't got one. I guess it depends on what network you're with? Data works fine for me currently.

A. Green
Fr/AM
OUR LIVING ROOM IS COMPLETELY FLOODED!!!!

A. Green
Fr/AM
AND AN ELECTRICAL POLE FELL ON OUR ROAD

Y. Park
Fr/PM
@Alexis Green you live on Beachfront Avenue right? My friend lives there and says the drains are blocked down the north end

B. Kendor
Fr/AM
Check your phone, emergency alert just came through about the reactor. if you aren't listening to local radio, they're saying we need to evacuate as the reactor could explode

A8

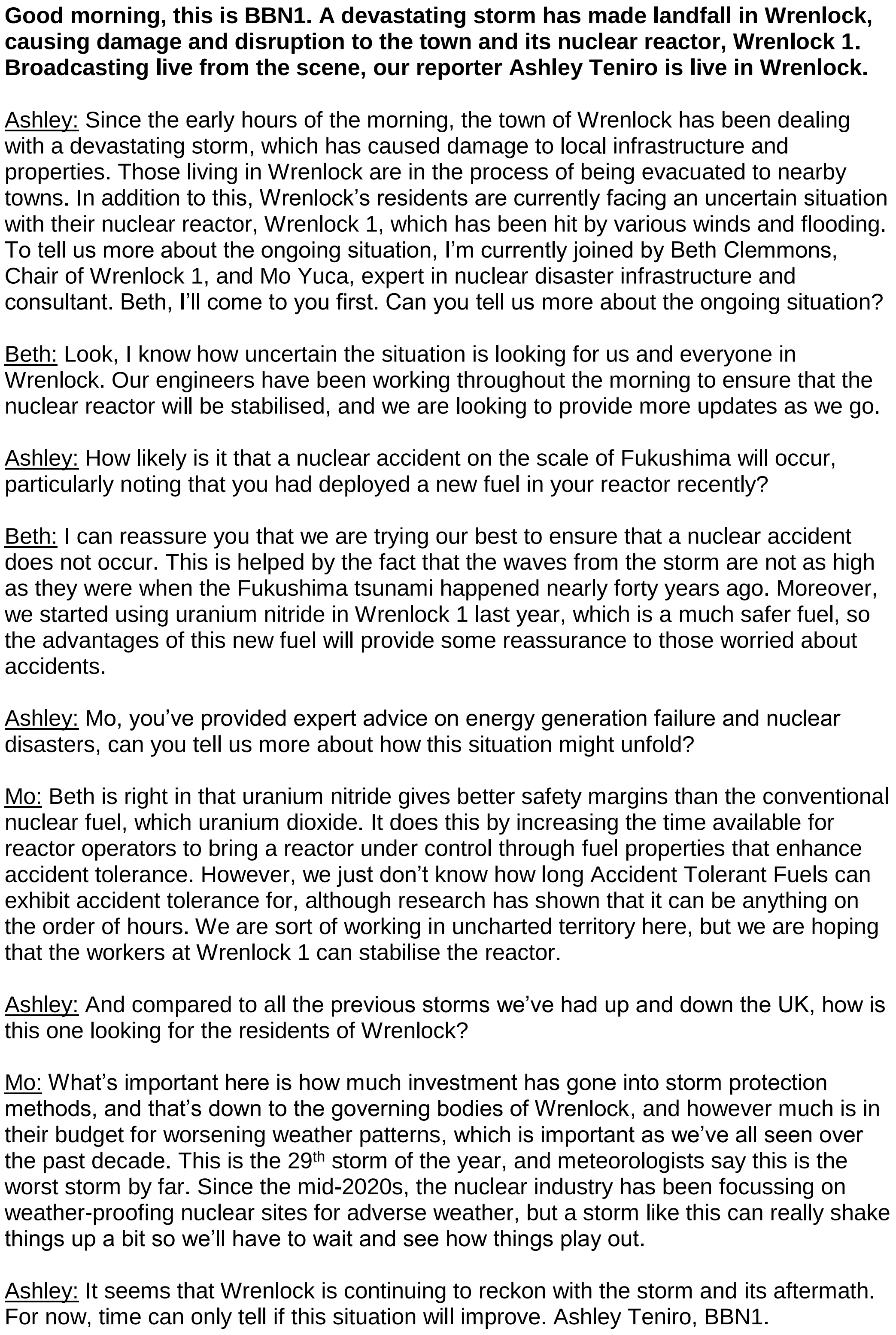
WRENL/2050/34
Diary entry donated and transcribed by Sebin Green, Wrenlock ex-resident

From "Exploring the Wrenlock Wreck" at NorthWest Museums

Dad woke me up this morning around half 3. Took essentials and the cat. Said something about the reactor exploding. Got in the car and drove (don't know where to) but roads are congested and there are only a few ways out of here. Really tired and don't know what's happening—feel really scared. Doesn't help that dad's constantly going on about how evil nuclear power is the whole way out of Wrenlock.

Don't have time to write more but hopefully everything will be ok.

A9



Good morning, this is BBN1. A devastating storm has made landfall in Wrenlock, causing damage and disruption to the town and its nuclear reactor, Wrenlock 1. Broadcasting live from the scene, our reporter Ashley Teniro is live in Wrenlock.

Ashley: Since the early hours of the morning, the town of Wrenlock has been dealing with a devastating storm, which has caused damage to local infrastructure and properties. Those living in Wrenlock are in the process of being evacuated to nearby towns. In addition to this, Wrenlock's residents are currently facing an uncertain situation with their nuclear reactor, Wrenlock 1, which has been hit by various winds and flooding. To tell us more about the ongoing situation, I'm currently joined by Beth Clemmons, Chair of Wrenlock 1, and Mo Yuca, expert in nuclear disaster infrastructure and consultant. Beth, I'll come to you first. Can you tell us more about the ongoing situation?

Beth: Look, I know how uncertain the situation is looking for us and everyone in Wrenlock. Our engineers have been working throughout the morning to ensure that the nuclear reactor will be stabilised, and we are looking to provide more updates as we go.

Ashley: How likely is it that a nuclear accident on the scale of Fukushima will occur, particularly noting that you had deployed a new fuel in your reactor recently?

Beth: I can reassure you that we are trying our best to ensure that a nuclear accident does not occur. This is helped by the fact that the waves from the storm are not as high as they were when the Fukushima tsunami happened nearly forty years ago. Moreover, we started using uranium nitride in Wrenlock 1 last year, which is a much safer fuel, so the advantages of this new fuel will provide some reassurance to those worried about accidents.

Ashley: Mo, you've provided expert advice on energy generation failure and nuclear disasters, can you tell us more about how this situation might unfold?

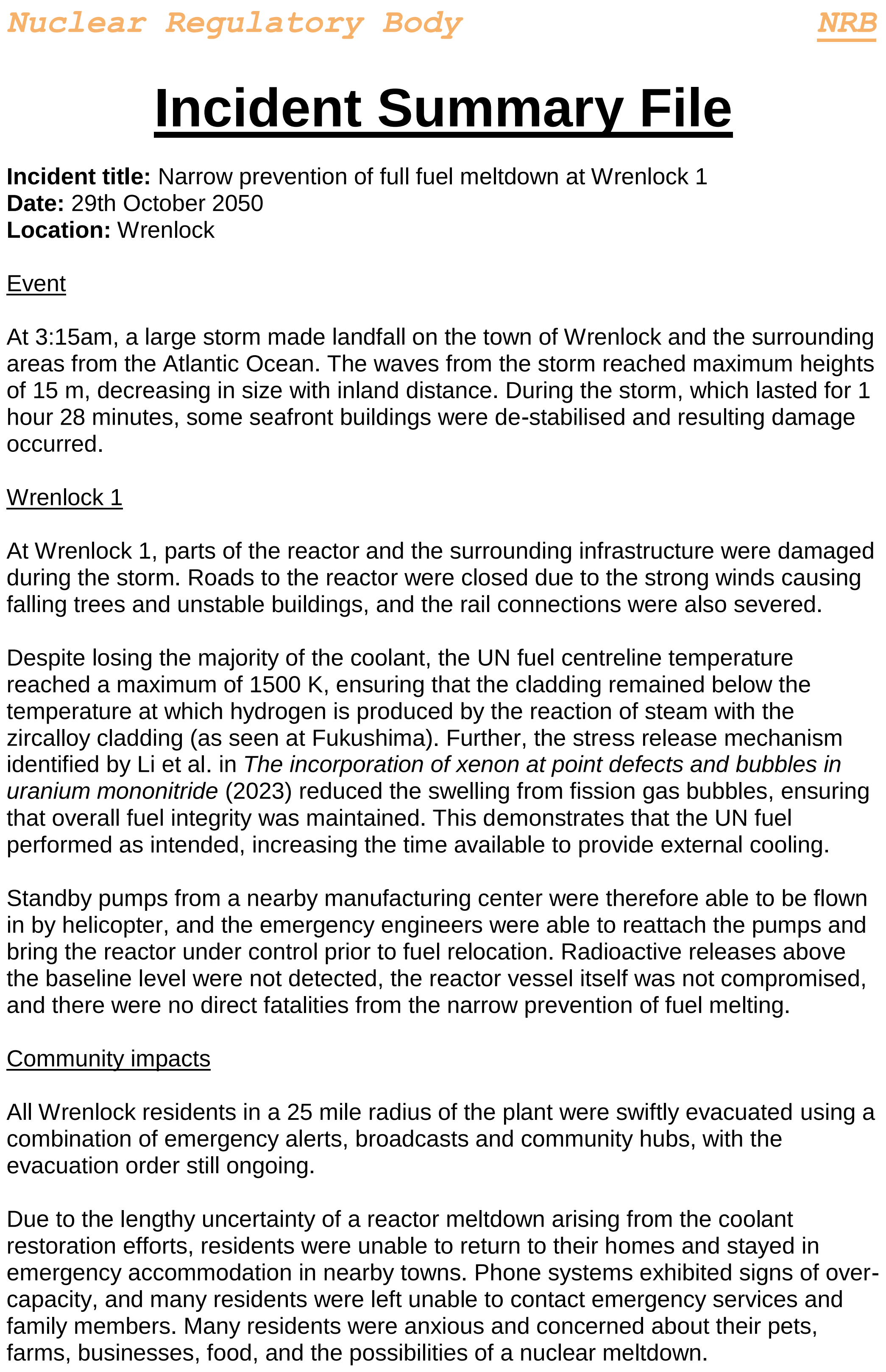
Mo: Beth is right in that uranium nitride gives better safety margins than the conventional nuclear fuel, which uranium dioxide. It does this by increasing the time available for reactor operators to bring a reactor under control through fuel properties that enhance accident tolerance. However, we just don't know how long Accident Tolerant Fuels can exhibit accident tolerance for, although research has shown that it can be anything on the order of hours. We are sort of working in uncharted territory here, but we are hoping that the workers at Wrenlock 1 can stabilise the reactor.

Ashley: And compared to all the previous storms we've had up and down the UK, how is this one looking for the residents of Wrenlock?

Mo: What's important here is how much investment has gone into storm protection methods, and that's down to the governing bodies of Wrenlock, and however much is in their budget for worsening weather patterns, which is important as we've all seen over the past decade. This is the 29th storm of the year, and meteorologists say this is the worst storm by far. Since the mid-2020s, the nuclear industry has been focussing on weather-proofing nuclear sites for adverse weather, but a storm like this can really shake things up a bit so we'll have to wait and see how things play out.

Ashley: It seems that Wrenlock is continuing to reckon with the storm and its aftermath. For now, time can only tell if this situation will improve. Ashley Teniro, BBN1.

A10



Nuclear Regulatory Body *NRB*

Incident Summary File

Incident title: Narrow prevention of full fuel meltdown at Wrenlock 1
Date: 29th October 2050
Location: Wrenlock

Event

At 3:15am, a large storm made landfall on the town of Wrenlock and the surrounding areas from the Atlantic Ocean. The waves from the storm reached maximum heights of 15 m, decreasing in size with inland distance. During the storm, which lasted for 1 hour 28 minutes, some seafront buildings were de-stabilised and resulting damage occurred.

Wrenlock 1

At Wrenlock 1, parts of the reactor and the surrounding infrastructure were damaged during the storm. Roads to the reactor were closed due to the strong winds causing falling trees and unstable buildings, and the rail connections were also severed.

Despite losing the majority of the coolant, the UN fuel centreline temperature reached a maximum of 1500 K, ensuring that the cladding remained below the temperature at which hydrogen is produced by the reaction of steam with the zircalloy cladding (as seen at Fukushima). Further, the stress release mechanism identified by Li et al. in *The incorporation of xenon at point defects and bubbles in uranium mononitride* (2023) reduced the swelling from fission gas bubbles, ensuring that overall fuel integrity was maintained. This demonstrates that the UN fuel performed as intended, increasing the time available to provide external cooling.

Standby pumps from a nearby manufacturing center were therefore able to be flown in by helicopter, and the emergency engineers were able to reattach the pumps and bring the reactor under control prior to fuel relocation. Radioactive releases above the baseline level were not detected, the reactor vessel itself was not compromised, and there were no direct fatalities from the narrow prevention of fuel melting.

Community impacts

All Wrenlock residents in a 25 mile radius of the plant were swiftly evacuated using a combination of emergency alerts, broadcasts and community hubs, with the evacuation order still ongoing.

Due to the lengthy uncertainty of a reactor meltdown arising from the coolant restoration efforts, residents were unable to return to their homes and stayed in emergency accommodation in nearby towns. Phone systems exhibited signs of over-capacity, and many residents were left unable to contact emergency services and family members. Many residents were anxious and concerned about their pets, farms, businesses, food, and the possibilities of a nuclear meltdown.

A11

WRENL/2050/81
Diary entry donated and transcribed by Sebin Green, Wrenlock ex-resident

From "Exploring the Wrenlock Wreck" at NorthWest Museums

The storm's still really bad. We are staying at dad's friend's place the next town over as our house is flooded. He's really nice and as we're not in the best state right now, he's been super understanding and he keeps offering us food and tea. It's a relief to finally be in a warm and dry space.

We made it out just after lunch yesterday, when the emergency services were there to coordinate everything. There were loads of road closures and damaged buildings that hindered our journey, but we managed to make it out. It was really chaotic, and the whole time my dad just kept saying "it's going to be okay, we're all going to be okay". We picked up some people along the way too who needed to get out of Wrenlock. At the moment I'm really tired and I really want to go home, but I'm just glad we made it out. On the way out, we talked to quite a few people and we kept on hearing whispers that there was a terrorist attack at the reactor done under the cover of the storm, but I think that was just a rumour.

Thankfully they managed to stabilise the reactor in time. They're saying that the near-miss was averted due to the new fuel. I think this is one of those things where you can't help but imagine what could have been. We could have all died... it's nuts—I started my internship 3 weeks ago, and I actually remember sitting in the break room talking about accident prevention with my Wrenlock 1 mentor, who was telling me about how the Fukushima accident happened and the aftermath—it's all just history to me, so it was interesting to learn about it. Who knew that here we would actually come close?

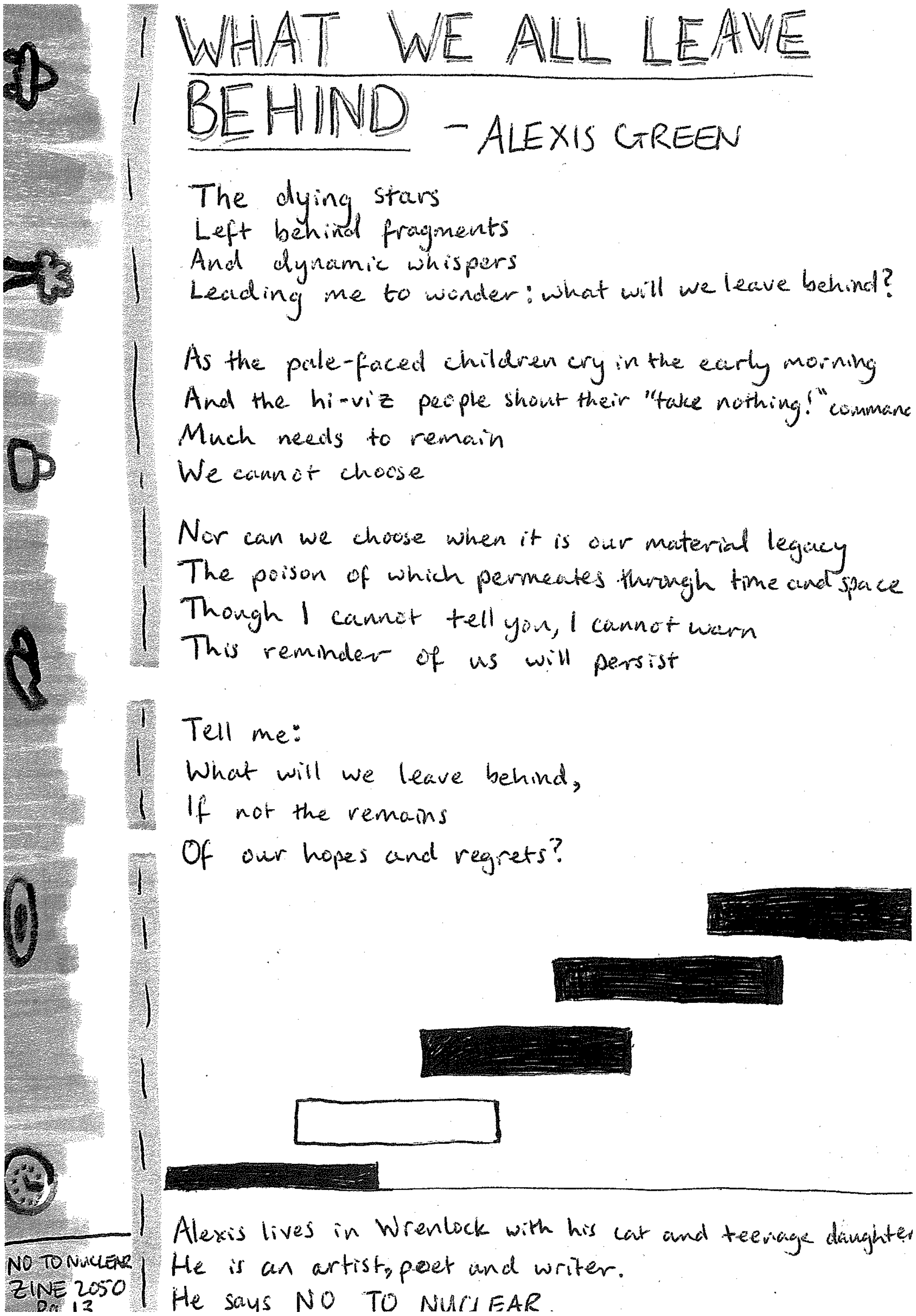
I think this near miss was the final straw for my dad. He's been switching from staring into space to angrily arguing with others on Canopy. He was really unhappy with me doing the internship because he detests nuclear power (something about grandma and her family being displaced from Fukushima?), but I think he wanted me to explore my options anyway—he says "this current climate is very unforgiving". We argued a lot over this, and I think I felt really cornered because he just assumes I don't know anything.

My friends at school are all scattered around, and I don't know when I'll see them next. It's hard to get in touch with them as well. School has been paused too, and there's no plans currently for alternatives to lessons. My Climate and Energy teacher, Dr Park, said she'd try and send out some materials soon. Dad and I have been arguing since this all started, and I think it's made our relationship really strained. It's like I'm just an extension of the nuclear industry to him. It may be too early to say, but things might not be the same again with me and dad.

A12

WRENL/2050/124
Poem in a “UNforgivable – no to nuclear” zine

From Wrenlock Community Archive



WHAT WE ALL LEAVE BEHIND

– ALEXIS GREEN

The dying stars
Left behind fragments
And dynamic whispers
Leading me to wonder: what will we leave behind?

As the pale-faced children cry in the early morning
And the hi-viz people shout their "take nothing!" commanc
Much needs to remain
We cannot choose

Nor can we choose when it is our material legacy
The poison of which permeates through time and space
Though I cannot tell you, I cannot warn
This reminder of us will persist

Tell me:
What will we leave behind,
If not the remains
Of our hopes and regrets?

Alexis lives in Wrenlock with his cat and teenage daughter
He is an artist, poet and writer.
He says NO TO NUCLEAR.

NO TO NUCLEAR
ZINE 2050
Pg. 13

TRANSCRIPTION

What we all leave behind – Alexis Green

The dying stars

Left behind fragments

And dynamic whispers

Leading me to wonder: what will we leave behind?

As the pale-faced children cry in the early morning

And the hi viz people shout their “take nothing!” commands

Much needs to remain

We cannot choose

Nor can we choose when it is our material legacy

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If not the remains

Of our hopes and regrets?

Alexis lives in Wrenlock with his cat and teenage daughter.

He is an artist, poet, and writer.

He says NO TO NUCLEAR.

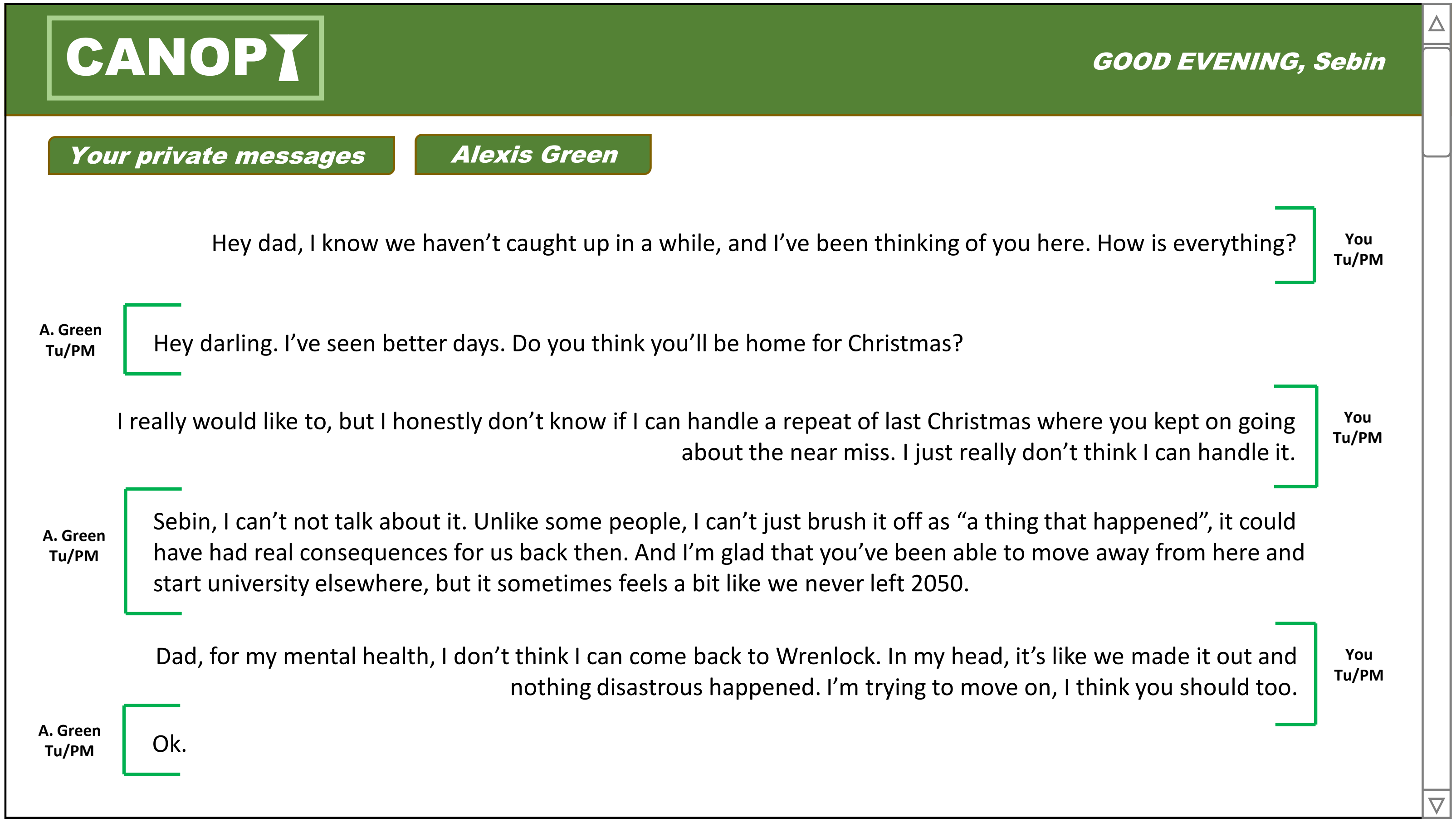
NO TO NUCLEAR ZINE 2050

Pg. 13

A13

2055

Reflections from afar



You Tu/PM: Hey dad, I know we haven't caught up in a while, and I've been thinking of you here. How is everything?

A. Green Tu/PM: Hey darling. I've seen better days. Do you think you'll be home for Christmas?

You Tu/PM: I really would like to, but I honestly don't know if I can handle a repeat of last Christmas where you kept on going about the near miss. I just really don't think I can handle it.

A. Green Tu/PM: Sebin, I can't not talk about it. Unlike some people, I can't just brush it off as "a thing that happened", it could have had real consequences for us back then. And I'm glad that you've been able to move away from here and start university elsewhere, but it sometimes feels a bit like we never left 2050.

You Tu/PM: Dad, for my mental health, I don't think I can come back to Wrenlock. In my head, it's like we made it out and nothing disastrous happened. I'm trying to move on, I think you should too.

A. Green Tu/PM: Ok.

A14

WRENL/2055/23
Diary entry donated and transcribed by Sebin Green, Wrenlock ex-resident

From "Exploring the Wrenlock Wreck" at NorthWest Museums

I think moving away for uni was one of the best decisions I've made for myself and I'm doing so much better than I was in Wrenlock, but my relationship with my dad is no better than it was before. It's like every single conversation with him needs to revolve around what happened with the storm and near miss, and it can't go any other way. I can't even talk about what's going on with us, with me, with the world, with him. He's like this on Canopy Wrenlock too. My therapist suggested that I do a thought exercise where I approach this from his point of view, imagining how his experience of it might cause him to think differently. I tried doing that a few times but I find that I'm having trouble talking to him and reconciling our views, because the conversation is always so focused on what happened back then.

I think that when I next go back to Wrenlock, I might try to help out at the Community Centre and help to repair the fractures running throughout the community since we've tried to rebuild after the storm. Maybe it might also get dad and I to understand each other. He was so disappointed when I left to study Nuclear Engineering but as far as I'm concerned, I really think I can improve things in the industry and maybe help him realise that there's more to nuclear than the bad things that have happened.

A15

Genetically altered sheep sets world record / Government Social Help voucher uptake low—PM backs initiative / Brazilian museum targeted by vandals

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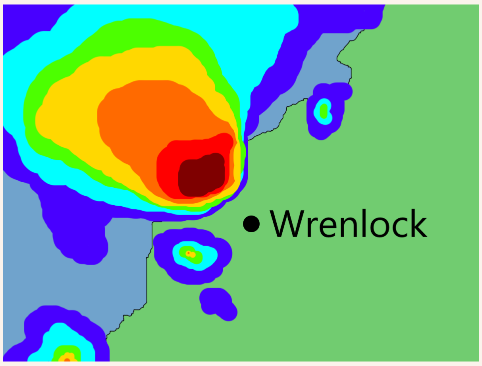
5 years on: the residents of Wrenlock on their "night of chaos"

Mugi Mozalk

Five years ago, gentle gusts over the town of Wrenlock became a harbinger for one of the most devastating and troubling incidents in north-west England.

Known as the "Wrenlock Wreck", it was the 29th storm of 2050, after a succession of increasingly destructive storms that struck the UK, due to erratic air currents.



A weather map showing the devastating storm approaching the coast of Wrenlock. Image: MapsNation

The storm approached from the Atlantic Ocean, and made landfall on the coast of Wrenlock at 3:15am, bringing top wind speeds of 102 mph.

Due to strong winds, some houses on the coast were torn apart, and others further inland had their roofing blown away. Electricity networks were also destroyed.

Concern quickly arose around Wrenlock's nuclear power plant, Wrenlock 1. Due to the impact of the storm partially wrecking reactor infrastructure, the reactor lost its coolant for around 15 hours, leading to poor fuel temperature regulation. Residents were swiftly evacuated from the town from the disaster and accident concerns.

However, the Global Nuclear Organisation (GNO) stated that an accident was averted due to a new type of reactor fuel which was instated into the reactor a year prior to the event.

Pol Tebris, Head of the GNO, says that "the properties of [the fuel] most likely prevented a catastrophe".

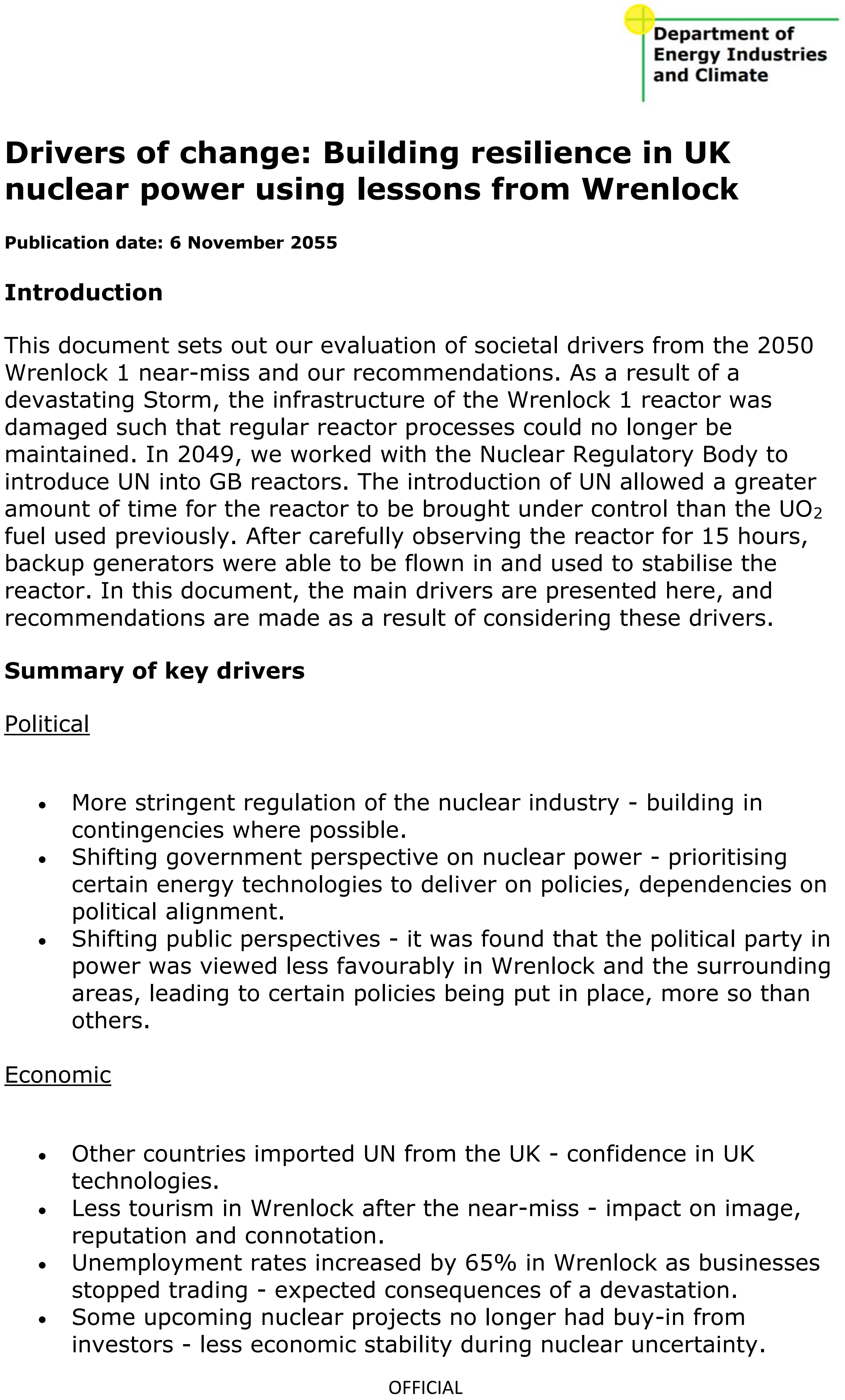
Despite this, the possibility of a nuclear accident unfolding became too much for some residents of Wrenlock.

Local resident Alexis Green claims that his relationship with his daughter, who is a trainee nuclear engineer, has been severed due to this, and says that "it was a night of chaos. Many of us were left in absolute and utter confusion during and after the evacuation, and the uncertainty over a nuclear accident only compounded my fears. It seems that we haven't learnt from Fukushima".

Others decided to move away from Wrenlock after the event. One anonymous ex-resident wrote in: "I don't think Beth Clemmons should have stepped down because it's harder to hold them accountable when sh*t goes down. I decided to leave because I wasn't convinced this wouldn't happen again". When contacted, a spokesperson for Wrenlock 1 has stated that "the incident was dealt with according to standard protocol".

A Government source says that greater scrutiny has been applied to the UK nuclear industry since the incident, and it is "working with all parties to ensure that we deliver Net Zero by 2075". The PM Ingrid Rosendhal is due to give a parliamentary announcement at 12pm to commemorate the incident, and honour all those affected by the event.

A16



Department of
Energy Industries
and Climate

Drivers of change: Building resilience in UK nuclear power using lessons from Wrenlock

Publication date: 6 November 2055

Introduction

This document sets out our evaluation of societal drivers from the 2050 Wrenlock 1 near-miss and our recommendations. As a result of a devastating Storm, the infrastructure of the Wrenlock 1 reactor was damaged such that regular reactor processes could no longer be maintained. In 2049, we worked with the Nuclear Regulatory Body to introduce UN into GB reactors. The introduction of UN allowed a greater amount of time for the reactor to be brought under control than the UO_2 fuel used previously. After carefully observing the reactor for 15 hours, backup generators were able to be flown in and used to stabilise the reactor. In this document, the main drivers are presented here, and recommendations are made as a result of considering these drivers.

Summary of key drivers

<u>Political</u>

- More stringent regulation of the nuclear industry - building in contingencies where possible.
- Shifting government perspective on nuclear power - prioritising certain energy technologies to deliver on policies, dependencies on political alignment.
- Shifting public perspectives - it was found that the political party in power was viewed less favourably in Wrenlock and the surrounding areas, leading to certain policies being put in place, more so than others.

<u>Economic</u>

- Other countries imported UN from the UK - confidence in UK technologies.
- Less tourism in Wrenlock after the near-miss - impact on image, reputation and connotation.
- Unemployment rates increased by 65% in Wrenlock as businesses stopped trading - expected consequences of a devastation.
- Some upcoming nuclear projects no longer had buy-in from investors - less economic stability during nuclear uncertainty.

OFFICIAL

Social

- Division in the Wrenlock community - impact on social dynamics during a nuclear uncertainty.
- Residents permanently moving away from Wrenlock following the evacuation - dissatisfaction and concern over the nuclear implications.
- Displacement had a profound effect on women, children, the elderly, the disabled, and the vulnerable - evacuation procedure not inclusive and clear enough.
- Annual remembrance of the event - keeping in touch with the past.

Technological

- AI technologies developed to assist in characterising the aftermath of storms - prevention rather than cure.
- Continued research into ATFs - constant progress into nuclear technologies.
- Impacts of other nuclear reactors under more scrutiny e.g. SMRs - incidents affecting other nuclear technologies.
- Nuclear industry developed better technological communication to connect with communities - constantly upgrading the nuclear industry’s technological relationship.

Legal

- Some residents sued - legal challenge from stakeholders in similar circumstances.
- Laws put in place to provide better transparency behind nuclear incidents - more protection for the people as opposed to energy companies.

Environmental

- Push for renewables - nuclear incidents negatively skewed by incident.
- Industry focus on natural disasters - more awareness on the potential devastation by other means.

Department of
Energy Industries
and Climate

DEIC recommendations

- Further engagement required with stakeholders - seeing the bigger picture.
- Embrace the inextricable relationship between the material and social aspects of nuclear power - using the key drivers to bring about change.
- Clearer incident processes are required from the nuclear industry - more engagement needed with the local community.
- More awareness education-wise - development of nuclear and futures literacy.
- Better horizon scanning and futures planning for nuclear reactors in the UK.
- Expand on successful implementation of new fuel – this event demonstrates the effective processes for the adoption of new nuclear technologies.

A17

WRENL/2055/34

Poem published in the Wrenlock Community Newsletter

From Wrenlock Community Archive (online)

Stopping

That night when the
Curtains of slumber
Were thrown aside
And normality was
Stopping.

The alarms were
Screaming and the
Emergency vehicles flew past and I felt
There was no
Stopping.

We go far
Far enough to escape
The horrors that would be unleashed
And we never knew if it would be
Stopping.

And what had defined
My child and me
Was about to
Stop.

That night

When there were would haves

Could haves

And should haves

And life had

For me

Stopped.

Alexis Green, December 2055

A18

6.3 Commentary on the artefacts

6.3.1 Reflections on the artefacts

The reasoning behind creating a future narrative using these artefacts lies in the capacity for artefacts to convey information and knowledge. By framing artefacts through an archival lens, this lends power to the artefacts and helps to enrich the backstory of Wrenlock and its residents. The creative, fictional elements of this story serve to speculatively mirror or challenge existing attitudes and perspectives in the context of this future world, allowing for a degree of freedom in exploring the material and social entanglements of nuclear power.

Various viewpoints were created and incorporated into the artefacts to show a diverse range of opinions that would emerge from events unfolding, and the voices that have been infused into the artefacts communicate a sense of identity and connection to environment and place. Immersion and estrangement has been integrated throughout the narrative; where the reader is able to immerse themselves and respond emotionally to an artefact, it is concurrently estranging for the reader in order to imagine this future. Furthermore, using characters and focussing on their empathic attachments by foregrounding their experiences is important for the reader's empathic identification to the future world and of perspectives different to their own.

Generally, the selection of the year 2050 as the temporal focal point for this story was due to it being a balanced middle ground between the familiarity of today's society, and the unknowns of a society in the far future. From this, I could more comfortably design and envision the societal changes that would and would not happen in this world – for example, social media would likely remain a large part of social connectivity, and how the characters would interact with each other. With many aspects of society remaining unchanged, I was careful to ensure that the artefacts were plausible to the reader to immerse them in the story, and that the character designs and story itself were realistic. Present throughout the artefacts is my own positionality[1]; Sharpe *et al.* note that "[a]ll research is socially constructed and observers are not independent from what is observed" [274]. Thus, my own experiences and understanding of the material social futures of nuclear power have been embedded in this work as a natural consequence of the research process.

The following commentary for these artefacts will cover the rationale for each artefact in the chronological order presented in this chapter, drawing from the themes encountered in this thesis to exhibit the entanglements of a nuclear future.

6.3.2 2049: A controversial arrival

The first artefact, **A1**, sets the scene using the front page of a fictional newspaper front page from 2049. Using a newspaper or other kinds of 'diegetic prototypes'[2] is an effective discursive device in speculative futures work to provide the reader with an immediate sense of time, place and established narrative, as well as to 'suspend disbelief about change' [592]. By setting the scene in this way, with the new development of UN, the reader understands the role of artefacts as modes of telling the story. In this newspaper article, the author seeks to inform a public audience of the mass production of UN, which the industry intends to use in Wrenlock's local nuclear reactor, Wrenlock 1. As well as immersing the reader through familiarity with newspapers, the fake newspaper article suggests the role of journalistic media in 2049: it is still consumed and used to disseminate events and information.

As well as introducing Wrenlock as a place – a coastal town with high unemployment rates – the newspaper article provides information about other details of this possible future. It indicates that in 2049, the society has become dietarily less

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[1] See Chapter 2.

[2] A diegetic prototype refers to an object that implicitly describes, through imagined narrative, another world. Diegetic prototypes can be in various forms, including but not limited to physical objects and audio-visual artefacts. It is often used as a design tool in speculative futures methods [592, 593].

meat-intensive, and also suggests that some of the UK's mid-twenty-first century's societal conditions have remained unchanged in terms of failing public transport and general economic difficulties. Building the world of Wrenlock involved asking questions: where is Wrenlock? Who lives in Wrenlock? What is the history of Wrenlock, and how has it changed in the future? The answers to these questions used my understanding of the present world and the environments I have experienced, and in turn helped to immerse the reader in the world of Wrenlock. Prior to this method of world-building, I had used the city-building game *i'm sorry did you say street magic* by Caro Asercion [594] to build a generic world expanded from a city, where descriptive prompts are used to construct perceptible neighbourhoods, towns, landmarks, and characters. However, I found that this did not work well for me in the near future; rather, it worked better in a far future or for a sci-fi or fantasy-like setting. Therefore, I needed to work with my own positionality rather than resist it when creating Wrenlock through these artefacts.

Alexis' poems, featured in all three sections (**A2**, **A13**, **A18**), give a sense of continuity and are windows to Alexis' character and personality. In particular, **A2** shows Alexis' uncertainty over the arrival of UN through the way he compares the fuel to an unknown new attendee at a party, and how his initial views changed from first impressions. I chose to present Alexis' poems as if they were curated archive artefacts from a specific collection. This type of narrative framing signifies the occurrence of a significant event—the "Wrenlock Wreck"—that makes the document part of a momentous moment in history, thus worth preserving for posterity. The poem is also on crumpled paper, retrieved from an "abandoned residence" after the event, which suggests that the Wrenlock Wreck caused massive destruction and disruption to the residents of Wrenlock.

Artefacts **A3** and **A4** are screenshots of a fictional social media site, "Canopy". The message exchanges shown here and in other Canopy posts have similarities to those sent and received on messaging platforms such as Whatsapp, Facebook, and Twitter, as well as local social media platforms such as NextDoor. However, Canopy is a purely text-based social media site that diverges away from most contemporary social media sites that involve images and videos, such as Instagram and TikTok. In this future, I have imagined that a group of people, tired of the consistently visual nature of social media, instead created a trend towards text-based social media. Although the reader would likely be familiar with what a messaging chain looks like and understand how an online conversation would progress, the fake platform itself, Canopy, lets the reader know that this conversation is situated in a different world, a speculative future. The Canopy messages are therefore an example of where I sought a balance between the familiar and the foreign, enabling the reader to remain engaged through immersion, and alienated through estrangement. Canopy also estranges the reader as I am diverging from the extrapolation of the present. I am incorporating elements of estrangement here by creating a message board that looks different from most contemporary social media platforms to challenge assumptions about how social media will develop in the future. In **A3**, we see Alexis communicate publicly with other members of the Wrenlock community on his disappointment around the implementation of UN. In the last message in **A3**, we see his personal reasons for opposing nuclear power and his emotional connections to Fukushima Daiichi, which contain the 'Fukushima happened, and...' motif that emerged in the Fukushima Daiichi thematic cluster in Chapter 3. The private messages in **A4** between Alexis and his daughter, Sebin, convey Sebin's mortification resulting from her father's comments on Canopy, and introduces and situates Sebin as a character in this story.

The following artefact, **A5**, is a transcript of a live interview conducted on programme by a national broadcaster, BBN1. The interviewer asks Beth Clemmons, the chair of Wrenlock 1, about the use of UN following the article in **A1**. Beth's style of voice and linguistic form have been modelled after the way senior figures in industry and politicians tend to speak in live interviews, in a manner that often skirts around difficult questions and highlights positive information to engender favourable public perceptions. In this artefact, Beth applies the 'Fukushima happened, but. . . ' motif, particularly in the response to the question referring to the Fukushima Daiichi nuclear disaster; this was included to emphasise how the nuclear industry in 2049 sees many opportunities arising from the accident. In comparison to Alexis in **A3**, Beth highlights the lessons learned from Fukushima Daiichi, rather than the further risks that had been uncovered by the accident, establishing for the audience a divide in the way certain characters think depending on their own contexts, experiences, and agendas. Artefact **A6** is a screenshot of a Canopy group chat featuring Sebin and her school friends. They discuss the live interview on BBN1, and are excited that something big is happening in their town. The plausibility of the artefacts needed to be considered, especially when writing in the style and voice of teenagers. Therefore, it was important to ensure that interactions between the teenagers were characteristically plausible; for example, emojis are used in messages, and I ultimately changed Sebin's message from calling the interview "cool" to simply commenting on the interview. Here, I lean on teenager attributes to signal that although Sebin is part of a friendship group that is interested in science, they are ultimately teenagers and would likely regard such an interview as unremarkable. In writing the teenage voice into this artefact, which I did so by drawing upon my experiences as a high school student, I am immersing the reader into this narrative through plausible scenarios.

As with many of Sebin's diary entries, artefact **A7** details her personal thoughts, albeit through an archival lens due to Sebin donating her diary entries at some point in the future to "NorthWest Museums". This entry details Sebin's encounter at school with her Climate and Energy class teacher, Dr Park, after Alexis' public exchange with her teacher on Canopy. Sebin briefly discusses HBO's *Chernobyl*—this was included in the diary entry to illuminate the notion that narratives do matter and have an impact on perceptions. Already, the reader perceives some tension between Sebin and Alexis from their different views on nuclear power. The entry also reveals Sebin's desire to pursue an internship in the nuclear industry at Wrenlock 1, and it unravels her feelings of boredom and loneliness from living in Wrenlock. The conflicts present in the narrative, such as the emotional friction arising from Alexis and Sebin's opposing opinions, are part of a wider representation of the multifaceted issues surrounding nuclear power. The characters become embodiments of differing views currently held of nuclear power around interlinked issues of safety, economic opportunities, and of generational differences. Through juxtaposing the characters' views, I was able to incorporate these pluralities into the narrative and reflect current attitudes towards nuclear power.

6.3.3 2050: Nuclear tempest

The first artefact of this section, **A8**, sets the scene for the beginning of the extreme weather event that this section focusses on. In **A8**, some residents of Wrenlock, awake in the early hours of the morning, are chatting on the local version of Canopy. They comment on the strength of the storm, and the residents share their experiences of the storm, which vary with their distance from the coast, where the storm is the most extreme—this is conveyed by the various degrees of nonchalance and anxiety in the messages. Alexis is panicked, as his living room is flooded due to the intense weather impacting his home situated beside the coast, and the surrounding infrastructure has begun to collapse. One resident shares the news that they need to evacuate due to the reactor being at a high risk of exploding. As a principal aim of employing UN in reactors is improving accident tolerance, I decided to expand upon what the social effects of the successful application of UN might look like. Therefore, I explored a potential catastrophe in this speculative future because it provided the stage for UN to serve its purpose, whilst allowing uncertainty and social anxieties around the outcome of using UN to be portrayed. After **A8**, the story then continues into **A9**, which sets out Sebin's point of view through her diary entry, written to detail her experiences during the evacuation. I wanted to evoke a sense of urgency by making this diary entry shorter to account for Sebin's feelings of panic and uncertainty during the evacuation. This artefact also deepens the cracks in Sebin and Alexis' relationship, which has been established in the previous section to be that of a fractured one, with generational conflict a defining characteristic of their relationship. I wanted to embed some intergenerational aspects of nuclear futures into the narrative to probe the way shifting times and changing attitudes occur, mirroring current generational differences, such as those belonging to Generation X and Generation Z, who have had largely different life experiences and different views on various issues. In order to include this in my narrative, I assume that the generational divides of the future will continue in the same way as they have done in the past and present. Through artefacts involving Alexis and Sebin, I am able to explore how social relationships are able to evolve due to the societal impacts of nuclear power; here, there is discord between Alexis and Sebin due to their differing personal meanings of nuclear power.

Artefact **A10** is a transcript of a BBN1 reporter describing the storm in Wrenlock, with a focus on the local reactor, Wrenlock 1. The reporter interviews Beth Clemmons and Mo Yuca in their professional capacities as leading voices in the industry to gain more insight on the storm's impacts for a public audience. This artefact was created to exemplify how an uncertainty with uranium nitride could be televised, especially involving an environmental disaster. Here, I tried to emulate the placating and assuaging tones that senior figures in industry tend to adopt in public interviews in order to avoid mass panic. The differences between the previous live interview on BBN1 in **A5** and this one include a slightly more critical tone of the nuclear industry through the direct suggestion that a new fuel would be responsible for any unfolding disasters. The inclusion of storm protection politics and mentions of a series of ever-worsening storms provides more depth to the the description of the incident, and assists with immersing the reader into the interview.

The following artefact, **A11**, is a one-page technical document summarising an accident near-miss at Wrenlock 1. The purpose of this artefact was to signal to the reader that an event involving Wrenlock 1 was taken seriously by the nuclear industry, who created this summary document a day after the near-miss, but that merely due to the ongoing investigation, the full details of the event are missing. In this artefact, the reference to my published paper featuring the work in Chapter 5 was designed to further emphasise the material-social entanglements of nuclear power, particularly in such circumstances where "Community impacts" are discussed in the artefacts. In my speculative future world, this artefact was produced by the fictional Nuclear Regulatory Body the (NRB), which I invented as a mirror of the Office for Nuclear Regulation, a nuclear regulator whose aim is to "protect society by securing safe nuclear operations" [595] . Including a fictional authoritative body in this narrative allows the reader to connect with an objective viewpoint of the near-miss and in turn consider their own reactions upon reading this artefact, connecting with Wrenlock residents through empathic pathways in the "Community impacts" section as well as what they have previously read of the residents' own experiences in previous artefacts.

Sebin's longer diary entry in this section, shown in artefact **A12**, describes her evacuation with Alexis and her feelings towards the near-miss. She identifies with experiencing the near-miss through listening to historical retellings of the Fukushima Daiichi accident, and describes her astonishment at the possibility of a reactor incident occurring. At the time of the evacuation, Sebin's feelings of fear and uncertainty are complex, especially considering her recently established ties to the reactor and nuclear power in general. The rumour of nuclear terrorism was included here to highlight the heightened social interconnectivity of people who are in alarmed states, and reflects Interviewee 8's comment on the destructive capacities of nuclear weaponry and the connotations of the term 'nuclear' in the Environment thematic cluster in Chapter 3. Later in the diary entry, Sebin describes the deterioration of her relationship with Alexis, and associates this with the near-miss and her seemingly betraying his values due to undertaking an internship at Wrenlock 1. However she does note his considerations for the poor socioeconomic climate in 2050, especially in the town of Wrenlock. Sebin's other relationships with her school friends and her education have also been affected by the evacuation, which she details in the diary entry to show the extent of the disruption caused by the evacuation. This artefact was predominantly created to exemplify the social uncertainties that materialise when technological uncertainties occur, and how the emotional shifts that take place during highly uncertain events are unchanging throughout history and the futures that we create.

The final artefact belonging to 2050 is **A13** – Alexis' second poem, "What we all leave behind". This artefact was created in a zine format, emulating the photocopied reproductions of independently-produced creative documents that are usually intended to be distributed by hand as a form of protest or expression of countercultural views. This implies the continuation of a similar mode of anti-nuclear expression in the UK as in the present, which is often situated outside of the mainstream. In his poem, Alexis describes the process of the evacuation and creates parallels between having to leave belongings in their home during the evacuation order and leaving nuclear waste behind for future generations. The zine format of **A13** allows the reader to consider Alexis' affective associations after the near-miss and to imagine him involving himself in collective action in the form of zine production. This artefact in particular is an example of how these artefacts help the reader to understand the motivations and mentalities of the characters, whilst maintaining plausibility; for instance, Alexis is an artist and he would likely participate in making a zine that aligns with his strong views around opposing nuclear power. In each artefact, the zest of each character is brought out in this way to immerse the reader in these futures and to enable them to better engage with the story.

6.3.4 2055: Reflections from afar

The title of this section refers to the sense of distance, both spatially (residents moving away) and temporally (revisiting the storm and near-miss five years later), that is common to these artefacts from 2055. The section begins with **A14**, which display a series of messages between Sebin and Alexis on Canopy. Five years after the event, Sebin and Alexis' relationship has diminished to infrequent contact, especially after Sebin has left Wrenlock to attend university in another place. Alexis asks Sebin whether she will be home for Christmas, but Sebin mentions the arguments that occurred between them the Christmas before. Being unable to reconcile their differences, the message chain ends inconclusively to show that their relationship in 2055 has become uncertain.

In **A15**, the reader understands through Sebin's diary entry that since moving away to attend university, she has been able to consider external viewpoints and an initial attempt to re-establish connections to the town she grew up in for the sake of the community and to better understand her father's values. It is revealed here that Sebin finished secondary school and went on to study Nuclear Engineering, a subject that is understandably at odds with her father's views – nevertheless, it is clear from A14 that Alexis earnestly continues to try and communicate with Sebin despite holding different opinions on nuclear power. However, in **A15**, this is evidently not always helpful in reconstructing Alexis and Sebin's relationship. Artefacts **A14** and **A15** were created as a somewhat inconclusive conclusion for the reader to learn how the primary characters in this story fare on diverging pathways, and to pull out Alexis and Sebin's relationship as a possible social future involving nuclear power.

Artefact **A16** shows the front page of The Alcoves, the same fake newspaper as featured in **A1**. Centred around the impacts of the Wrenlock Wreck, the journalist describes the storm that occurred at Wrenlock in 2050 and the impacts on Wrenlock 1, and gathers a variety of views from the nuclear industry, the Government, and

Alexis. This artefact reveals more information on the events of the near-miss, and how certain groups have or have not been affected by it. The scale of the near-miss is also indicated here through the inclusion of a political response suggesting interest at a national level. Insights into the sociopolitical and environmental climates in 2055 are also shown in **A16**; given that the Prime Minister mentioned a "Net Zero" goal by 2075, this largely echoes the current sociopolitical and environmental climate in the early 2020s and exemplifies the usage of present knowledge and understanding to build future worlds. Furthermore, I wanted the storm to be an indication of the worsening effects of the climate crisis by 2050, as this estranges the reader from present-day complacency about climate change.

The following artefact, **A17**, is a policy document from the fictional Department of Energy Industries and Climate, created by the department to reflect on the drivers of the near-miss and to suggest policy recommendations. This artefact differs from **A11** in that the technical summary report in **A11** was created shortly after the event, and hence lacked the full analytical details as **A17**. The societal drivers mentioned in **A17** have more detail due to the retrospective evaluation of the near-miss allowed with the abundance of time, and attempt to capture the sentiments in a succinct fashion using the PESTLE framework[3]. This artefact serves to exemplify the governmental connections to nuclear power, and the ensuing opportunities for action and progress in these future societies governed by bodies similar to those in the present.

It is in the final artefact – **A18** – where the reader is able to perceive a sense of closure to the story through Alexis' poem "Stopping". In this poem, which was featured in Wrenlock's community newsletter, Alexis communicates his inability to feel in control of when the near-miss occurred and the aftermath, indicating how the event became a psychological burden for him. Simplistic in tone, Alexis's poem

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[3] As discussed in Chapter 1.

shows to the reader that he continues to remain drawn to the events of 2050, and that his relationship with Sebin had altered drastically as a result. As a stopping point for this story, Alexis' poem is not necessarily a definitive end; rather, it invites the reader to consider the future beyond 2055, and the avenues through which many more relationships are able to be reshaped due to the narratives of nuclear power in their own imagined worlds.

6.4 Conclusion

These artefacts, examined in an almost anthropological manner in this chapter, have shown the opportunities inherent in purposely highlighting the entanglements of the material and the social in uncertain futures. In creating these artefacts, I have ventured outside of my positionality and my own understanding as a materials science researcher to explore the social interconnections of nuclear power, and the way the present informs how the future is perceived.

Through focussing on identity and place in a future world, the reader has been able to immerse themselves in the story, whilst the estranging aspects of the artefacts have enabled the reader to defamiliarise themself with the present in order to engage with futures. The artefacts in this chapter are not solely examples of the way material and social futures are intertwined; they represent real opportunities for all researchers to embrace the complex entanglements of their work and think differently about certain topics from how they would usually think about them, i.e. through journal articles and strictly academic work. Through creating characters and organisations for the story, I have been able to incorporate various voices into the conversation, drawing on the many voices that I have interviewed for this thesis. Combined in this way, these artefacts have shown the strength of futures thinking when used to tackle current issues, compared with the deficiencies of relatively insular policy documents.

It is only natural to draw out the emerging themes from any creative-critical futures work. If we are to assume that Alexis and Sebin are paradigmatic for future generational relations, then above all, I have created a narrative of intergenerational conflict arising as a result of the material social futures of nuclear power. This implies a certain trajectory in terms of public opinion—towards greater acceptance of nuclear power—but it is complicated by the subtext of the increasing impacts of climate change. Therefore, the narrative highlights the future entanglements of nuclear power through the overarching themes from the amplification of the current social narratives of nuclear power.

As always, the process of making the artefacts and the artefacts themselves could be improved. By integrating more characters into the story, the complexities of future societies and the interactions within could be explored. Additionally, although the future presented in this chapter has been conceptualised solely by myself, there is scope for this process to be extended to others as part of a collaborative futures-building exercise, for example, with the interviewees.

This thesis, which focusses on general nuclear materiality as an exploration of material social future entanglements, uses the material developments of UN to probe the social futures of nuclear power, thereby necessitating this chapter of creative-critical work. The research presented in Chapters 4 and 5 are examples of the progression of nuclear materials, and to show how developing research on ATFs and knowledge of accident scenarios can influence future eventualities. I hope that this chapter in particular, and the narratives I have created, will be read as an exploratory possibility for the future of nuclear power, rather than as a strict allegory. I also hope that through interacting with this particular material social future, other materials scientists are inspired to divert from their rigid disciplinary norms and forge narratives using their work to explore their own material social futures. If this practice is increasingly taken up, the complex entanglements within our world will be better understood, and we will in turn better understand our material social futures.

Ultimately, this chapter shows that building an example of a future narrative of nuclear power has added another dimension to the way we think and communicate about nuclear power through the immersion and estrangement that artefacts generate for the reader. The culmination of the work in this thesis has been as a result of making temporal leaps: from the present, to the past, to the present, to the future, and so on and so forth. By examining where we were positioned in our histories, we can decide on the actions we wish to pursue in order to shape the futures we desire, and for a materially significant subject like nuclear power, the social entanglements that exist must undoubtedly continue to be a key part of decisions involved in shaping that future.

In this chapter, I presented a nuclear future to ultimately show that my research question (*"Can a creative-critical future be produced using a Material Social Futures perspective, and what will that look like?"*) has been answered with art and with a futures-facing perspective. This chapter leads towards the conclusion of this thesis in the next chapter, as can be seen from Figure 6.1.

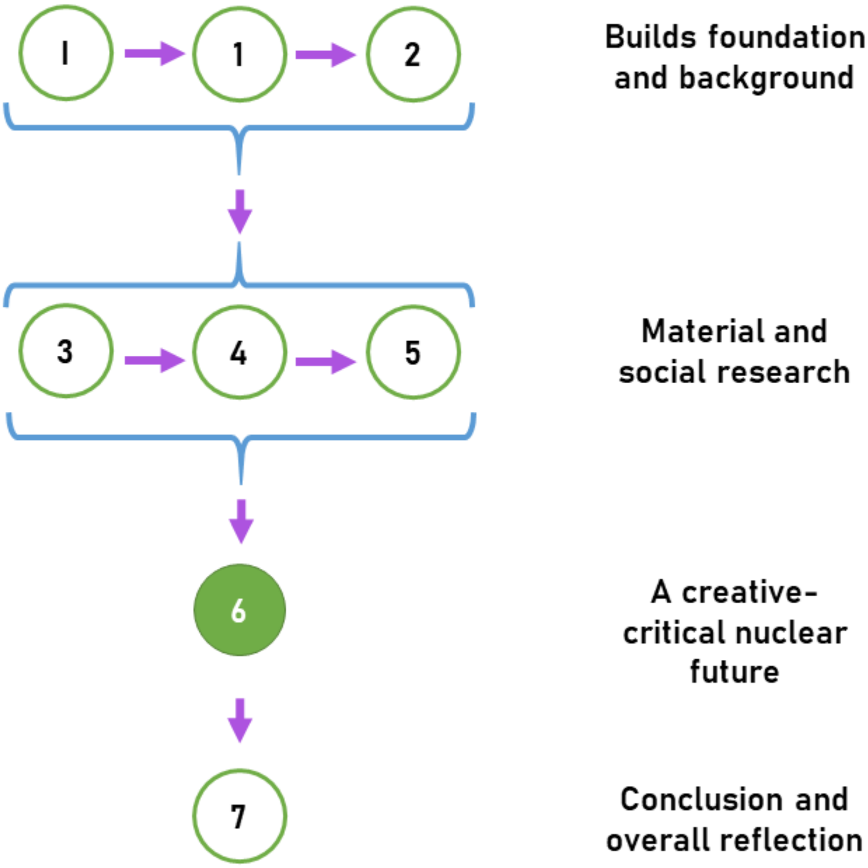

Figure 6.1: A map of the thesis structure. The chapter that we are in now (‘6’) contains a creative-critical future.

Chapter 7

Conclusion

My research in Chapters 3, 4, and 5 culminated in the previous chapter, in the creative-critical future. As can be seen in Figure 7.1, the thesis has been built up using the background and context of nuclear power, and uses the findings in the material and social research chapters to rationalise the nuclear future set out in Chapter 6. In this chapter, I will summarise and reflect on this journey, and provide commentary on limitations and interdisciplinary research.

Through adopting an interdisciplinary Material Social Futures approach in this thesis, the amalgamation of different frameworks from often separated academic disciplines, as well as the sustained attention to the current narratives and discourse on nuclear power, has produced more insightful and holistic perspectives into nuclear power overall.

Within the overall themes of this thesis, which include material consciousness and affective attachments to nuclear power, the original contributions of this research have been exhibited in each chapter. The social dimensions of nuclear power were explored in detail in Chapter 3, where archival material relating to nuclear power was used as a basis for formulating interview questions to be used in semi-structured interviews with various stakeholders, such as sector employees and anti-nuclear campaigners. From using Discourse Analysis to extract meaning from the interviews,

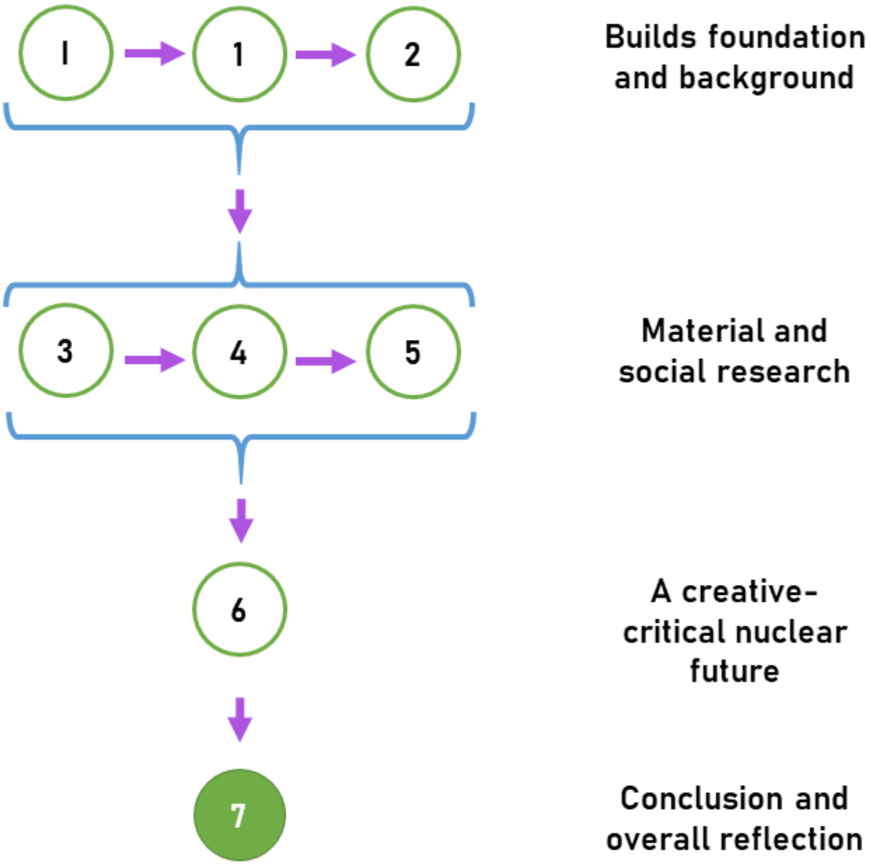

Figure 7.1: A map of the thesis structure. The chapter that we are in now (‘7’) concludes the thesis and contains reflections of my journey.

four key thematic clusters were identified: Environment; Fukushima Daiichi: a case study; Attitudes and attachments; and Discourse and narratives. Pivoting to a material approach to nuclear materialities, the thermophysical properties of hypo-stoichiometric UN have been simulated in Chapter 4 through introducing nitrogen antisites and nitrogen vacancy defects in the UN lattice. From this, the activation energies for nitrogen diffusion in hypo-stoichiometric were found to have excellent agreement with experimental observations, where increased nitrogen diffusivity corresponded with lower activation energies. Building on the findings in Chapter 4, Chapter 5 focussed on fission gas evolution, specifically the growth of xenon bubbles in voids in the UN lattice. Here, it was found that high bubble densities, the xenon atoms crystallise in an fcc arrangement, and that at sufficiently high temperatures, bubble size, and bubble pressure, loop punching occurs as a result of the UN lattice preferring to deform instead of integrating the xenon atoms. Finally, in Chapter 6, I presented artefacts belonging to a speculative world set around 2050 to explore a specific possible future of nuclear power and to exemplify how adopting interdisciplinary futures thinking methods in academic disciplines assists researchers with navigating the complexities of material-social entanglements.

Together, these chapters encapsulate the essence of interdisciplinary thinking and research, and highlight how narratives and materials are interwoven throughout history and in futures, as well as the impacts and reliance between the material and the social. The materials science work in this thesis shows the limits and opportunities of what is actually technically possible in terms of the development of the material aspects of nuclear power. The exploration of nuclear materials informs many areas of social policymaking, as no decision around risk aversion can be debated without a clear view of what is materially possible. On the other hand, the qualitative social explorations of my thesis show that research into materials themselves is only useful to an extent, whereafter questions around concerns regarding nuclear power, risk and safety, and the history of nuclear accidents must be included in the discussion. As a consequence, conducting research through an interdisciplinary lens is of great value and importance in relation to thinking about nuclear futures. By deliberately taking this intellectual approach in my working, I have been able to comprehensively examine nuclear energy futures, which are fraught and uncertain, by taking into account what nuclear power means and has meant to people, to humans with complex emotions and thoughts. If I had exclusively adopted a material or a sociocultural lens, it would automatically give an incomplete and unbalanced picture, and prevent positive interventions in energy futures that would make nuclear power safer and steer us away from over-reliance on fossil fuels.

Some limitations of the work in this thesis relate to the relative lack of simulation data for UN compared to UO_2 that would have aided in my computational studies. Due to the relative lack of experimental research into UN and the insufficient quality of available data, I was unable to extensively validate some of my research. Additionally, quantitative data could have offered more insight into social perceptions of nuclear power. However, limitations open up avenues for further work; for example, the diffusion of xenon and other fission gas atoms and bubbles could be investigated, as well as the interactions between fission products and the effects of different stoichiometries. For my futures work, I could have explored alternative scenarios and incorporated other tools used by futures scholars—for example, I could envision how various nuclear futures may emerge as per the Three Horizons method. The multiplicity of creative-critical futures could also be further explored by involving stakeholders in the exercise for continuity.

In a wider setting, the implications of my work are manifold. The evolution of this research has been such that initially, it was planned to focus mostly on nuclear material science with some commentary on the social facets of nuclear power, and eventually became a comfortable balance between the material science and the social science and humanities. As I began undertaking more of the materials science research, it became more and more apparent to me that the sociocultural aspects around nuclear power needed to feature more strongly in my thesis in order to unravel the values and meanings materials have in society. As a result, it became organically necessary to adopt an interdisciplinary approach in my research journey, and so the portion of the qualitative social sciences work grew. The knowledge gained in the technical chapters has changed the purpose and depth of the futures work in Chapter 6—from understanding how UN behaves, the artefacts have been materially situated. One example of this is using the knowledge of how fission gas atoms behave in UN to justify, in a live interview, the nuclear industry's increased confidence in the Wrenlock 1 reactor in an accident scenario. This approach has become a powerful example of how interdisciplinarity is able to yield greater impacts and increase the inherent value of a researcher. The findings in this thesis show that it is important to find deeper understanding and detail to any material and social interface, and in particular, highlights the need for nuclear specialists to be conducting and engaging with futures such that their expertise can be properly contextualised when designing energy futures.

Overall, by using the power of mixed methods in both qualitative and quantitative approaches, I have foregrounded the interdisciplinarity that must be afforded for material science research, and exemplified the importance of being conscious of entangled futures. This is especially the case as our currently siloed methods are insufficient for planning our energy futures; science and society can no longer be separated, and hence interdisciplinarity is needed to expand our viewpoints and conduct research in a more holistic manner. As we head deeper into the abyss of the climate crisis, the social dimension and political ecology of nuclear power must not be ignored in our pursuit for societal growth and progress—instead, further exploration of material social futures is encouraged in order to fully embrace the complex entanglements at the heart of living and being with materials.

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Appendix A

Details of Ethical Approval

Ethical approval was obtained from the Faculty of Science and Technology Research Ethics Committee (ref: FSTREC20004). After contacting various organisations via email to gather expressions of interest, interviews were arranged with willing participants. Consent forms, formal invitation letters, and participant information sheets were distributed by email, the latter two of which are detailed in the below sections.

A.1 Example Formal Invitation Letter

Dear Pete,

I am writing to invite you to participate in online interviews to offer your views on nuclear power as part of my PhD research project in Lancaster University's Material Social Futures programme, which looks at the roles and positions developing technologies play in a future society.

I would like to invite you to these online interviews, conducted over Microsoft Teams, on **26th May 2021**, starting from **9:30am**. These recorded interviews will involve a series of questions revolving around your views surrounding nuclear power, and will be conducted by myself. Your ideas and thoughts will help shape my research into the futures of nuclear power, and to identify roots of concern pertaining to the nuclear power industry.

I appreciate your participation in these interviews. If you have any questions in the meantime, please do not hesitate to get in touch at j.li74@lancaster.ac.uk.

Kindest regards,

Jade

A.2 Participant Information Sheet

See overleaf.

Department of Engineering, Lancaster University

Participant information sheet

For further information about how Lancaster University processes personal data for research purposes and your data rights please visit our webpage: www.lancaster.ac.uk/research/data-protection

I am a PhD student at Lancaster University and I would like to invite you to take part in a research study about perceptions towards nuclear power in and around the industry.

Please take time to read the following information carefully before you decide whether or not you wish to take part.

What is the study about?

This study aims to understand perceptions towards nuclear power, as well as perceived relationships between workers in the nuclear industry and anti-nuclear activists.

Why have I been invited?

I have approached you because I have identified you as a key stakeholder either in or around the nuclear power industry, and I am keen to understand a range of views towards the nuclear industry. I would be very grateful if you would agree to take part in this study.

What will I be asked to do if I take part?

If you decided to take part, this would involve sharing your views by participating in interviews, where a series of questions will be asked about yourself and your involvement in the nuclear industry. The length of the interview could be between 30mins – 1hr.

What are the possible benefits from taking part?

Taking part in this study will allow for your views to contribute to my understanding of relationships with and around nuclear power, and this may help to shape the future of the nuclear industry.

Do I have to take part?

No. It’s completely up to you to decide whether or not you take part. Your participation is voluntary and you are free to withdraw at any time, without giving any reason.

What if I change my mind?

If you change your mind, you are free to withdraw at any time during your participation in this study. If you want to withdraw, please let me know, and I will extract any ideas or information (=data) you contributed to the study and destroy them. However, it is difficult and often impossible to take out data from one specific participant when this has already been anonymised or pooled together with other people's data. Therefore, you can only withdraw up to 6 weeks after taking part in the study.

What are the possible disadvantages and risks of taking part?

It is unlikely that there will be any major disadvantages to taking part, however, interviews may be lengthy, possible around 2 hours.

Will my data be identifiable?

Before the interview, you will be asked whether your data can be directly attributed to you.

You have two choices pertaining to this:

1) Everything you say and your name/affiliation will be included in my research outputs
2) Everything you say will be published but will not be attributed to you, i.e., you will be anonymous.

After the interview, only I, the researcher conducting this study will have access to the ideas you share with us, along with my supervisors and other members of my research team. As the interviews will be recorded, the only other person who will have access to what you contributed is a professional transcriber who will listen to the recordings and produce a written record of what you have said. The transcriber will sign a confidentiality agreement

How will my data be stored?

Your data will be stored in encrypted files (that is no-one other than me, the researcher will be able to access them) and on password-protected computers. In accordance with University guidelines, I will keep the data securely for a minimum of ten years.

How will we use the information you have shared with us and what will happen to the results of the research study?

I will use the data you have shared with only in the following ways:
I will use it for academic purposes only. This will include my PhD thesis and other publications, for example, journal articles. I may also present the results of this study at academic conferences. When writing up the findings from this study, I would like to reproduce some of the views and ideas you shared with us.

Who has reviewed the project?

This study has been reviewed and approved by the Faculty of Science and Technology Research Ethics Committee.

What if I have a question or concern?

If you have any queries or if you are unhappy with anything that happens concerning your participation in the study, please contact myself, Jade Li, at:

j.li74@lancaster.ac.uk. Alternatively, you can contact my supervisor, Dr Emily Spiers (e.spiers@lancaster.ac.uk, +44 (0)1524 593564, Department of Languages and Cultures, Lancaster University, LA1 4YD).

If you have any concerns or complaints that you wish to discuss with a person who is not directly involved in the research, you can also contact: Professor Richard Harper, r.harper@lancaster.ac.uk, +44 (0)1524 593105, Room 56, InfoLab 21 Building, South Drive, Lancaster University, Lancaster LA1 4WA.

Sources of support

If you are affected by any issues that may arise in the interview process, support is available online (https://www.nhs.uk/conditions/stress-anxiety-depression/mental-health-helplines/) and through Counselling and Psychotherapy (https://www.bacp.co.uk/).

Thank you for considering your participation in this project.

Appendix B

Background Information on Interviewees and Organisations

Brief descriptions of the organisations which the interviewees belong to are provided below. The backgrounds of all eight interviewees are listed, detailing their affiliation, role, and any other relevant information. Anonymous interviewees are denoted with a number.

B.1 Organisations

- **Together Against Sizewell C (TASC)**: A Suffolk-based campaign group established in 2013, protesting against new nuclear builds along the Suffolk coast.
- **Mothers for Nuclear**: A US-based environmental organisation founded in 2016, advocating for an increased role of nuclear power in protecting both children and the environment.
- **Supporters of Nuclear Energy (SONE)**: A UK-based campaign group supporting nuclear energy and its role in sustainable economic development, founded in 1988.

- **United Kingdom Atomic Energy Authority (UKAEA)**: A government organisation formed in 1954, carrying out research in nuclear fusion technologies. Based in Culham, Oxfordshire, and sponsored by the Department for Business, Energy & Industrial Strategy (BEIS).

- **Nuclear New Build Generation Company (NNB GenCo)**: A UK subdivision of EDF Energy concerned with building four new reactors at Hinkley Point C (HPC) and Sizewell C (SZC). EDF Energy, which is a French company, created NNB GenCo after acquiring British Energy in 2009.

- **Nuclear Legacy Advisory Forum (Nuleaf)**: A UK-based organisation founded in 2003 working with local governments in England and Wales on the issue of nuclear legacy, including waste management and decommissioning.

- **Nuclear Free Local Authorities (NFLA)**: An organisation consisting of councils and other local government groups in the UK that have adopted anti-nuclear policies. Established in 2009.

B.2 Interviewees

- **Janet Fendley**: An anti-nuclear campaigner in TASC who lives locally to the Sizewell nuclear reactors.

- **Kristin Zaitz and Heather Hoff**: The founders of Mothers for Nuclear. Both working nuclear professionals at the Diablo Canyon nuclear power plant in California, Kristin is a civil engineer and Heather is a reactor operator.

- **Pete Wilkinson**: The chairperson and secretary of TASC, co-founder of Friends of the Earth and an establishing member during the emergence of Greenpeace UK. Consultant to Radioactive Waste Management Ltd.

- **Wade Allison**: An Emeritus professor of Physics at Oxford University, author of several published books in support of nuclear power including *Radiation and*

Reason: The Impact of Science on a Culture of Fear and *Nuclear is for Life: A Cultural Revolution*. Honorary Secretary of SONE.

- **Interviewee 5**: Works in communications at the UKAEA.
- **Interviewee 6**: Works in communications at NNB GenCo (Sizewell C).
- **Interviewee 7**: Works in Nuleaf.
- **Interviewee 8**: Works in policy in the NFLA.

Appendix C

Aide-mémoire

An aide-mémoire, listed below, was constructed to guide the interview topics in a semi-structured manner, which involved asking questions centred around fixed themes and following up on interesting or relevant details; it was important that this did not become a stringent process as I wanted the interviewees to explore different avenues of thought around each topic.

1. Introduction, explaining interview and recording consent
2. Interviewee background
3. Recent interactions with opposing groups
4. Feelings towards the opposing groups
5. Media portrayal of nuclear energy
6. Drivers for relationship with nuclear power
7. Thoughts around the Fukushima-Daiichi accident
8. Hypothetical scenario - technological solution to Fukushima-Daiichi accident
9. Impact of hypothetical scenario on future relationships with nuclear power
10. Possible roles of nuclear power in future energy landscape

11. If you could send a message to the people of the future about nuclear power, what would it be?
12. Conclusion, wrapping up

The interviews were recorded over Microsoft Teams, and was transcribed by Maggie Lackey of ML Transcriptions. The recordings and their transcripts were secured, along with the consent forms and other relevant data, on my university OneDrive, as agreed on with Lancaster University's ethics committee.

Appendix D

Transcript coding

Coding was carried out on the interview transcripts to allow for detailed discourse analysis to take place. For this, I manually scanned the text and extracted certain words and phrases according to certain aspects that were exhibited, detailed below with examples from the interviews:

- **Key word, key phrase** - “Waste", “The more I learn the more I am a supporter"
- **Pronoun** - “Our greatgrandchildren"
- **Context** - “Welsh lamb. Wales getting more rainfall"
- **Semiotics** - “Web of concern"
- **Attitude:**
  - **Affect (emotions felt)** - “I just remember feeling so frustrated"
  - **Judgement (of people’s behaviour)** - “I hope and pray that common sense kicks in"
  - **Appreciation and valuation (of ‘things’)** - “Very delicate sensitive habitat area"