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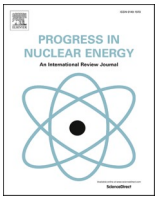

Radiophobia: Useful concept, or ostracising term?

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ABSTRACT

The term 'radiophobia' has been a cornerstone in the nuclear discourse over the past 70 years. It has been used extensively to dismiss fears of radiation as being emotional overreactions to a risk that is actuarially very low, stemming from public ignorance. Despite its longevity, little attention has been afforded to the term, its history, and the factors that underpin the extreme divergence in risk perception that the term de facto refers to, threatening to severely hamper any efforts to redress said divergence. This article will explore these factors, mostly sociopsychological in nature, and conclude that the powerful affective imagery associated with radiation, compounded by various heuristics and biases, renders public discomfort with ionising radiation from nuclear power plants rational – despite the actuarial safety record of nuclear energy globally. The article will note that, whilst its often ostracising usage towards the public should render the term obsolete, radiophobia can still be regarded as a useful concept to try and explain the extreme risk perception divergence that exists between nuclear experts and the public. However, in order for a more constructive nuclear discourse, a paradigm shift will be required, acknowledging the complex historical and sociopsychological factors that have shaped radiation into becoming a uniquely feared process. Such an acknowledgement will likely be a prerequisite for any efforts towards normalising humanity's relationship with radiation, and would require considerable changes in communication practices.

1. Introduction

Suicides, abortions, stigmatisation, depression, anxiety, bullying – the consequences of radiophobia are significant and can be severe. The fear of radiation is well documented, as are its impacts. Despite the fact radiophobia as a phenomenon has been clearly observed since the atomic bombings of Hiroshima and Nagasaki in 1945, very little progress towards resolving it has been made. This became especially evident during and following the Fukushima Daiichi accident in 2011, highlighting a systemic failure to get to grasp with the concept of radiophobia, and its psychological roots. To most observers of the nuclear debates over the decades, radiophobia is almost like an old friend. Indeed, as one travels through the roughly 125 years of human interactions with ionising radiation, the footprints, and the shadows of radiophobia are abundant. It is well established that there exists a major risk perception gap as far as radiation is concerned, both between subject matter experts and the public (both relating to nuclear power accidents and different radiation sources) (Slovic, 1987, 1996; Litmanen, 1996; Fox-Glassman and Weber, 2016; Palfreman, 2006; Allen, 1996; North, 1999) but also between different professions (e.g. physicists, engineers and chemists ranking nuclear risks significantly lower than biologists or biomedical researchers) (Barke and Jenkins-Smith, 1993). Whilst scientific knowledge about the health effects of radiation exposure has grown considerably since its discovery in 1895, the perception gap remains. Despite considerable efforts having been dedicated to attempt to alleviate public concerns about any potential health consequences of exposure, it is evident that this has not been successful. Indeed, it is rather remarkable that more than 125 years of public awareness of radiation has not translated into any major shifts in its risk perception profile. It can be argued that at its most fundamental, radiophobia is the offspring of this gap, fuelled by the invisibility of radiation which, inherently, makes it malleable to influences, both internal and external. To date, the different factors that does give rise to, and reinforce, radiophobia have only been tangentially explored, resulting in a weak conceptualisation of radiophobia. In turn, this has had a negative impacts on how this risk perception discrepancy is handled, let alone addressed.

Furthermore, radiophobia as a term has acquired a troubling guise,

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having been used extensively in debates pertaining to the use of nuclear technologies as a shorthand to dismiss concerns or fears raised by the public. Whilst the considerable harm caused by radiophobia is well established, the sociopsychological nature of these consequences has often resulted in them being dismissed as emotional and irrational. This theme of "irrationality" is deeply rooted within parts of the nuclear community, and has for decades exerted considerable influence over the overall engagement with the general public. Paul Slovic, the pioneer psychologist who laid much of the groundwork in the risk perception literature, aptly summarised how the nuclear industry historically has *"… express[ed] great consternation and antagonism toward a public they view as "ignorant", "radiophobic" or "irrational""* (Slovic et al., 2000). Indeed, as noted by Roeser (2011), *"there seems to be one constant factor in the [nuclear] debate … proponents call opponents badly informed, emotional, and irrational …"* (Roeser, 2011). This highlights not only a poor understanding amongst the nuclear industry of the nature of the relationship that most humans have with radiation, but also the underlying psychosocial processes that underpins this relationship.

This paper, therefore, seeks to address some of these shortcomings, by offering a holistic reappraisal of radiophobia as a concept, and the underlying processes that has made humanity's relationship with radiation largely unique amongst the many carcinogens that exists, as well as an assessment as to whether radiophobia can still be used constructively. However, in order for such an assessment to be conducted, radiophobia must be properly defined.

2. What is radiophobia, actually?

Radiophobia has become shorthand for a sentiment that regards any fear of ionising radiation as an emotional gut reaction largely disconnected from scientific facts. In many situations, this fear has been minimized by professionals to ensure the benefits of radiation can be maximized. However, despite its widespread usage - a quick Google search shows how the term has proliferated, with more than 56,000 hits - there seems to be little uniformity in how the term is used, let alone defined; indeed, there is often no definition even offered. Indeed, the analysis of radiophobia as a phenomenon has, however, been done with little robustness. This lack of robustness is highly problematic, as it leaves considerable space for interpretation and undermines any opportunity for a holistic analysis. Most of the existing literature on radiophobia [see e.g. 12, Myslobodsky, 2001; Novikau, 2017] offers merely cursory or partial explanations as to its emergence and persistence, often citing factors such as links with nuclear weapons or the regulatory environment as driving the development of radiophobia.

The term radiophobia, being a portmanteau of "radiation" and "phobia", invariably invites the comparison with clinically significant phobias such as arachnophobia or hemophobia. However, when comparing the fear of radiation that is commonly encountered with the clinical criteria (as set out by the 5th edition of Diagnostic and Statistical Manual of Mental Disorders (DSM-5), it is clear that radiophobia fundamentally is a misnomer. Whilst some of the criteria could, at a glance, seem to fit the phenomenon – e.g. a *"marked fear or anxiety about a specific object or situation"* (American Psychiatric Association, 2013) – it is evident that the phobia argument does not withstand scrutiny. For instance, no anxiety or (self) stigmatisation is seen as a result of the continuous exposure of radiation from natural sources – which in some geographies exceeds the global average radiation dose considerably (Ali et al., 2020; Hendry et al., 2009). Indeed, there is a very clear distinction being made between different types of radiation exposure, with mostly radiation from nuclear power plants eliciting a powerful reaction (in some clinical settings, anxiety sometimes manifest amongst patients and staff, resulting in hesitancy or avoidance of certain diagnostic tests or treatments (Siegel et al., 2017a; Siegel et al., 2017b; Lopes et al., 2021; Oakley and Harrison, 2020)). However, the clearest criteria that confirms the conclusion that radiophobia is not a clinical phobia is found in the following diagnostic criteria for phobias: *"fear or anxiety is out of proportion to the actual danger posed by the specific object or situation* ***and to the sociocultural context*** *[authors' emphasis]"* (American Psychiatric Association, 2013). When drawing upon findings in fields such as social psychology, neuroscience, sociology, cognitive science, and anthropology, the fear of radiation is not out of proportion with its sociocultural context, but rather makes sense and is rational, based on the radiation discourse and its place within public consciousness. Indeed, a radiophobic response is entirely in line with expectations, following decades of discursive, social, and cultural priming which has greatly increased the perceived risks associated with radiation. However, having ruled out the notion of radiophobia as being a clinical phobia, it does beg the question: how can radiophobia be defined?

There is one commonality that often can be found in the use of radiophobia: fear. This also acts as a suitable starting point in offering a definition of the term. Humans are born with very few fears (these include falling/loss of balance (Gibson and Walk, 1960) and loud noises (Valentine, 1930; Yeomans and Frankland, 1996)), but most fears are socialized, and are inevitably shaped by perceptions (and sometimes, experiences). The question of perception, and the behaviours it drives, is central to the proposed definition of radiophobia. Indeed, it is long since established that there exists a major divergence in risk perception as far as radiation from nuclear power plants is concerned (Slovic, 1987, 1996; Litmanen, 1996; Fox-Glassman and Weber, 2016; Palfreman, 2006; Allen, 1996; North, 1999; Brook, 2012). Whereas actuarially nuclear power is the safest energy source currently in use (UNSCEAR, 2008; Markandya and Wilkinson, 2007; UNSCEAR, 2013; UNSCEAR, 2021; Vohra, 2021; Richie, 2020), the risk posed by nuclear power (accidents) is perceived by members of the public to be much higher. Herein lies the proposed definition of radiophobia, as being *"the socio-psychological and cultural relationship between individuals and ionising radiation, characterised by a clear disparity between the actual and perceived risks and health effects of radiation exposure"*. With this definition in mind, it is time to explore where radiophobia came from.

3. Where did radiophobia come from?

The first time radiophobia was mentioned in printed form was (likely) in 1903 in the Los Angeles Times (The Los Angeles Times, 1903); however, instead of referring to ionising radiation – which had been discovered seven years earlier by Wilhelm Roentgen – it referred to radio waves and radios. This would remain the case for the next 50 years, before mentions of radiophobia would be made in direct connection with radiation, as seen in an article in the Medford Mail Tribune from 1960, stating that *"Many Americans Claimed Suffering From Radiophobia"* (Medford Mail Tribune). Since then, its use proliferated. A commonly-encountered explanatory model for the emergence of radiophobia – and often cited by commentators – was the linking of radiation with the risk (and impacts) of nuclear war (Ropeik, 2016), especially during the periods 1946–1965 and 1980–85. This finds some support in the literature, especially with the discursive linking of nuclear weapons and nuclear power which, to some degrees, did share similar vocabularies and imagery (Shigemura et al., 2021; Slovic et al., 1985; Smith, 1988; Ho et al., 2019). Indeed, Slovic et al. (1991) found that the perceived aftermath of a nuclear accident that was being described during interviews was very similar to that of a nuclear explosion (Slovic et al., 1991). However, as clearly shown by e.g. Lavine (2013), the antecedents of radiophobia can be firmly traced back to the 1930s, potentially even earlier (Lavine, 2013).

The potential negative health effects of ionising radiation became evident merely months following its discovery (Jorgensen, 2016). Skin erythema became closely related with X-rays, which gives some indication of the doses ($\geq$2Gy to the skin) often involved in the early days of using X-rays in a range of applications. However, whilst the early X-ray machines often were intimidating, making loud noises and electricity sparking, there was initially little to suggest that radiophobia would emerge. Indeed, it could have been reasonable to expect that radiation

would have gone down a similar path as electricity which, during its early days, caused considerable anxiety and concern (Wills, 2021; Sullivan, 1995; Gooday et al., 2011). Considerable efforts were dedicated to showcasing the importance of electricity, which also did achieve normalisation of electricity. Similarly, e.g. Marie Curie's mobile X-ray clinics during World War I proved an early confidence boost for the public perception of radiation. Whilst the duality that nowadays is associated with radiation – the power to heal (e.g. radiotherapy for cancer treatments or diagnostic X-rays) or the power to kill (e.g. radiation exposure causing cancers or Acute Radiation Syndrome) (Weart, 1988, 2012) – would only start to emerge following a number of scandals involving radiation, antecedents of this duality can still be detected in the 1910s and 1920s (Lavine, 2013).

One of the most well-known examples of radiation-induced injuries that played a foundational role in shaping the nascent radiophobia was that of the so-called "Radium Girls". From the end of World War I until the latter half of the 1920s, two American companies sold self-luminous watches, with a paint that used powdered radium. In order for the paint to be applied to various parts of the watch, female factory workers would use their lips to shape the brush, thus ingesting small amounts of radium. Eventually, many of the women started to exhibit a range of symptoms in relation to this ingestion, such as anaemia, oral lesions, dental wounds refusing to heal, suppression of menstruation, sterility, and necrosis of the jaw – a symptom that would become dubbed a "radium jaw" (Gunderman and Gonda, 2015; Moore, 2016). Whilst it is unknown how many women suffered injury or died due to radium ingestion and the associated radiation injuries, the ensuing litigation and extensive media coverage would bring these women and their injuries into the limelight. Their injuries were described in gruesome detail, and played an instrumental role in providing early imagery of radiation as an insidious, unseeable risk that would cause significant suffering. This base image remains strong to this day, highlighting the importance of the case of the "Radium Girls" in shaping public perception and narratives.

The second influential case that aided in reinforcing the early imagery of radiophobia was that of the American socialite and sportsman Eben Myers (1880–1932) (Macklis, 1993). In 1927, in response to an arm injury, he began to take daily doses of the patent medicine Radithor, which contained the isotopes radium-226 and radium-228. Over the next three years, he consumed between 1000 and 1500 vials of Radithor (International Atomic Energy Agency, 2014), before stopping in 1930. In 1931, when Byers failed to appear in front of the Federal Trade Commission, the lawyer that visited him noted that *"[h]is head was swathed in bandages. He had undergone two successive operations in which his whole upper jaw, excepting two front teeth, and most of his lower jaw had been removed. … All the remaining bone tissue of his body was slowly disintegrating, and holes were actually forming in his skull"* (Time Magazine, 1932). Byers' illness and subsequent death by the cancers caused by his ingestion of radioactive materials were extensively covered by the press (Anonymous, 1932a, 1932b, 1932c), and took place following the stories of the "Radium Girls", further reinforcing the often-gruesome imagery that radiation began to be associated with. These two examples showcase the transformation that radiation underwent, from having earlier been regarded as the panacea, to becoming - at best - a necessary evil, was completed even before the start of World War II, let alone by the atomic bombings in 1945.

The upcoming decades would, nevertheless, play a major role in reinforcing the groundwork laid pre-WWII, and brought radiophobia to new levels. The events at Hiroshima and Nagasaki doubtlessly provided vivid imagery that would come to be used in nuclear discourse, as well as provided a first example of widespread radiophobia. The period from the end of World War II until the late 1950s was marked by increasing anxieties about nuclear technologies and radiation, but there was still a strong notion of duality, with nuclear representing either a bright future, or the newfound ability to destroy humanity within hours (Weart, 1988, 2012; Gamson and Modigliani, 1989; Hohenemser et al., 1977; Lindberg, 2016). Whilst nuclear weapons did not create radiophobia, they brought it to a new level, as it turned the threats of radiation from facing a few individuals, mostly working with radiation, to virtually all of humanity. The issue of fallout from nuclear weapons testing would come to play a significant role in shaping the radiophobic narrative that still ensues. For instance, Sternglass (1969) contented in a piece for Esquire Magazine - titled "The Death of All Children" - that some 400,000 children had died as a result of radiation from fallout (Sternglass, 1969). Radiophobia's impact on policymaking became clear for the first time in the early 1960s. The Baby Tooth Survey, organized by the St. Louis Committee for Nuclear Information, collected some 320,000 children's teeth to measure the accumulation of strontium-90 as a result of fallout from atmospheric testing of nuclear weapons (Alvarez and Mangano, 2021). The fact that radioactive elements were accumulating at detectable levels in humans, and several "milk scares" with fallout being measured in milk caused considerable discomfort (Whitehurst, 2021). This was aided by campaigning by a number of vocal scientists, such as the Nobel laureates Linus Pauling and Hermann Muller. Both argued passionately against nuclear weapons (Rubinson, 2011), with Pauling writing that *"… the fission products in radioactive fallout from the bomb tests to date will in the course of generations cause the birth of 80,000 children with gross physical or mental defects, 300,000 to die at birth or in early childhood, plus 700,000 embryonic deaths"* (Linus Pauling to Robert Gilmore, 1958). Such statements invariably helped to shape the image of radiation as posing a major threat to public health (although they rarely quantified the doses necessary, or the methodological uncertainties that are inherently linked to the exposure of low radiation doses). Similarly, Muller was instrumental in replacing the notion of there being radiation exposure thresholds, beneath which no negative health effects, with the Linear No Threshold (LNT) model that argued there would be no safe levels of radiation (Calabrese, 2018). This paradigm shift proved very influential in the history of radiophobia. When the National Academy of Science released their report on the genetic effects of radiation exposure in 1956, the New York Times ran *"Scientists term radiation a peril to future of man"* (Leviero, 1956) on their front page. Whilst there is not a scientific consensus on whether or not LNT is correct (for reviews on the low-dose controversy, see e.g. Calabrese (2017a, 2017b), Mossman (2011), Sykes (2020), and Boice (2017)), such statements, in conjunction with the fact children's health was perceived to be in danger, helped to cement radiophobic narratives. These narratives exerted huge influence on policy, with e.g. the Baby Tooth survey playing an important role in persuading President Kennedy to push for the Partial Test Ban Treaty (Whitehurst, 2021).

With the moratorium on, and subsequent banning of, atmospheric tests in 1963, the focus turned towards nuclear power and its potential radioactive releases, especially during an accident (Weart, 1988, 2012; Gamson and Modigliani, 1989; Hohenemser et al., 1977). Many of the sensitivities that the fallout controversy had heightened prevailed as the discourse was largely transplanted from nuclear weapons to nuclear power (Lindberg, 2016), with radiation acting as a bridge between the two. Claims similar to those made during the fallout debate surfaced around nuclear power, stating that if every individual absorbed the maximum radiation exposure from nuclear power plants, allowed by regulatory limits, the ensuing collective dose would be considerable and, consequently, the regulatory authorities approved hundreds of thousands of deaths annually (Rossin, 2003). Even if these claims were untrue, it helped establish a narrative of immense danger from radiation. Indeed, that narrative remains, with nuclear energy being perceived as having the potential to bring death and suffering on such an immense scale that no possible actions could be undertaken in order counteract it (Trombetta, 2008). By the mid-1970s, the discourse had turned decidedly radiophobic, and the accident at Three Mile Island in 1979 did showcase just how sociocultural influences and risk perception play out as radiophobia. For instance, whilst a very limited evacuation recommendation was issued by Governor Dick Thornburgh for pregnant women and pre-school age children, it was estimated that almost 200,

000 people left the area (Cutter and Barnes, 1982). This reaction was exacerbated by the media coverage, which relied heavily on radiophobic materials, largely aided by the release of the Hollywood film "The China Syndrome" 12 days prior to the accident (Wills, 2006; Malmsheimer, 1986). Other factors, such as sensitivities about the health of children (born or unborn) and pregnant women played a major role; however, these concerns were doubtlessly enhanced by latent radiophobia and the radiophobic discourse that surrounded the issue. Three Mile Island was the first indication of the fact that when something goes wrong at a nuclear power plant, the emotional responses, driven by radiophobia, is considerable. All subsequent nuclear accidents confirm this. Indeed, when the Chernobyl accident took place in 1986, the accident merely "proved" just how dangerous nuclear power could be. Sensationalist news coverage, using language such as a *"nuclear nightmare"* which required *"suicide squads on the edge of hell"* to combat the fires at Chernobyl with 100,000 certain to die (Herbert, 1987), further cemented radiophobia. Following Chernobyl, the consequences of radiophobia started to show on a significant scale, and these sociopsychological effects were recognised early on as requiring attention (The International Chernobyl Project, 1991; European Commission et al., 2006). Whilst it is pertinent to recognise that other factors, including evacuation, will have played a role in these negative health impacts, radiophobia nevertheless was a key driver behind such policies and thus indirectly exerted additional pressure on individuals. When the accident happened at Fukushima Daiichi following the Great Tohoku earthquake and the ensuring tsunami, it became very evident that many of the identified lessons from Chernobyl (Slovic, 2012; Renn and Institut, 1988; Renn, 1990; Hecla et al., 2020; Kasperson, 2012) had not been incorporated, especially in relation to radiophobia-driven behaviours and health detriments. Indeed, with the exception of radiophobia-induced abortions (Ishii et al., 2017; Fujimori et al., 2014; Leppold et al., 2017), the public responses (and consequences) were largely identical. The evacuations that took place during the early phases of the accident resulted in 2259 premature deaths, with analysis suggesting that the danger of the rapid evacuation was higher than the risk posed by radiation (Fukushima Prefectural Government 2018 Steps, 2018; Murakami et al., 2015; Waddington et al., 2017), further noting the detrimental impacts of radiophobia. Furthermore, much of the media coverage of the accident recited radiophobic assertions around the health impacts of radiation exposure (including exaggerating the potential risks associated with doses far below natural background), further highlighting the fact that any attempts by the nuclear power community to address radiophobia had been unsuccessful.

With this history in mind, it is essential to look at the socio-psychological processes that has resulted in the emergence and entrenchment of radiophobia at both individual and societal levels.

4. What drives radiophobia?

Some explanations for the drivers of radiophobia – such as social stigmatisation due to perceived contamination (Erikson, 1991) – have previously been offered by researchers and commentators. Attempts have also been made to integrate the imagery of especially nuclear power (and radiation) with radiophobia (Weart, 1988, 2012). However, efforts to date have not accounted for the many socio-psychological processes that underpin human behaviours and decision-making and how they specifically interact with radiation. This is a shortcoming that this paper seeks to address.

It is long established that human decision-making is imperfect, being characterised by what Simon (1957) dubbed "bounded rationality", whereby different constraints (e.g. cognitive or temporal) limits rationality (Simon et al., 1990). In other words, factors beyond facts and logic often determine the way humans perceive and interact with their surroundings. Research efforts, spearheaded by e.g. Kahneman and Tversky, have established that human thoughts are broadly formed in one of two "systems". "System 1" can be characterised as fast, automatic, emotional, biased, unconscious and stereotyping, whereas "System 2" can be characterised as slow, effortful, calculating, conscious and logical (Kahneman, 2011). It is estimated that some 95% of all interactions with the surrounding environment is dealt with by "System 1", using images, narratives and metaphors to encode the way reality is perceived (Slovic et al., 2004). Images, irrespective of whether they are actual, recalled from memory, or symbolic, are the basic building blocks to the conscious and subconscious mind (Damasio, 2000), playing a key function in both perceptual-motor and cognitive tasks (Marks, 1999). Indeed, the ability to create visual imagery becomes central irrespective of *"whether it is the everyday problem-solving required for stability, safety, and survival at home, in the workplace, or in the community"* (Marks, 2019). These images do not exist in a vacuum, however, and are embedded within a matrix of emotions and affect, which is crucial for effective decision-making. Historically, the role of emotions has been regarded as merely irrational gut reactions, and been positioned in a dichotomous relationship against rationality, as suggested by some (Haidt, 2001). However, it is important to stress that affect cannot be used to dismiss risk perceptions as "irrational" or "emotional" (Sjöberg, 1996). On the contrary, with the brain being hard-wired to place emotions and imagery at the heart of the engagement with surrounding environments, affect and emotions become central to decision making (Reynolds, 2011). Furthermore, it has been found that individuals with certain types of brain damage struggle to make decisions when their emotional function has been damaged (Damasio, 1996, 2006). The "somatic marker" hypothesis is particularly useful as a conceptual vessel for the drivers of radiophobia, as it argues that images acquire a variety of feelings ("somatic markers") that can be either positive or negative. These markers are, in turn, linked to a battery of physical reactions. Indeed, as highlighted by Damasio (1996), *"… when the somatosensory which defines a certain emotional response is juxta-posed to the images which describe a related scenario of future outcome, and which triggered the emotional response via the ventro-medial linkage, the somatosensory pattern marks the scenario as good or bad"* (Damasio, 1996). The images and associated somatic markers (whose intensity varies in strength) are subsequently pooled, and are consulted in future decision-making (Slovic et al., 2005). When an individual encounters an image or situation associated with a negative marker, it is likely that awareness and alarm would increase, whereas encountering an image associated with a positive marker would more likely act as an incentive (Damasio, 1996, 2006).

An important factor explaining the emergence and subsequent stability of radiophobia is the fact human perception is largely blind to probability. Instead, the possibility of a risk materialising is a significant driver in terms of perception (Loewenstein et al., 2001; Rottenstreich and Hsee, 2001; Slovic et al., 2007). In the case of radiation, the mere possibility that radiation exposure – irrespective of the actual dose – can cause cancer, congenital defects, and hereditary impacts, is enough to shape public perception to such a degree where these outcomes become virtually certain if exposed. Once such a notion has become embedded within both an individual's mind and in the broader collective narrative, it becomes very challenging to dislodge it, especially as it begins to acquire affective imagery and other associations that, in turn, becomes embedded and reinforced by a variety of mental shortcuts (heuristics) and biases.

Thanks to its invisibility, radiation must be "made visible" in order for a meaningful relationship to be developed. Popular culture exerts immense influence on the way humans conceptualise and relate to the world, and its potential to shape political and social agendas is well-documented, especially within the nuclear realm (Renzi et al., 2017; Falkof, 2013; Gamson and Modigliani, 1989). With very few direct experiences with radiation, popular culture's influence become doubly important for understanding of radiation discourse and the way it shapes radiophobia. Since the very beginning of humanity's relationship with radiation, the number of interpretations of radiation has proliferated, resulting in a vast and colourful canon of imagery. Nevertheless, some commonalities in the discourse became evident early on, and central to

this is the notion of prying at, and subtly changing, the most basic building blocks of life: the double helix that makes up DNA. This has been translated into second-order narratives that is prominently featured in popular culture, often populated by mutated beings and with messages – both spoken and subliminally – framing radiation as an existential threat to humans both alive and unborn (be it cancers, birth defects, or hereditary impacts). Increasing the potency of this imagery and their somatic markers, and acting as a central driving force behind radiophobia, is the availability heuristic. It is defined as tendency to make *"… judgments about likelihood of occurrence in which the individual bases such judgments on the salience of the information held in his or her memory about the particular type of event …"* (American Psychological Association, 2021c). Given the general strength of the somatic markers associated with radiation imagery, it is not unreasonable to assume that these will be readily available when related to a nuclear event. Indeed, given the highly publicised nature of any (perceived) nuclear or radiological or nuclear incident or accident, the availability heuristic does exert considerable pressure to reinforce radiophobic behaviours and decisions, as it relies on imagery taken straight out of a strongly radiophobic discourse which, in turn, is heavily influenced by popular culture.

A second heuristic –anchoring bias – is also of significance for radiophobia. The American Psychological Association defines anchoring biases as *"the tendency, in forming perceptions or making quantitative judgments under conditions of uncertainty, to give excessive weight to the starting value (or anchor), based on the first received information or one's initial judgment, and not to modify this anchor sufficiently in light of later information"* (American Psychological Association, 2021b). As already noted, radiation as a perceived phenomenon is very influenceable, thanks to its invisibility. Other factors, such as the inherent uncertainties, and lack of direct attributability, related to (potential) health impacts of especially low dose exposure, as well as the broad unfamiliarity with radiation, also strengthens the impact of anchoring bias in relation to radiophobia. As most people do not have any direct experience with radiation, their perceptions are influences by the anchoring bias. Indeed, in the majority of cases, the only relationship that an individual will have with either radiation or nuclear power is through media coverage or, more likely, popular culture portrayals. The images and the often sensationalistic nature of any news related to nuclear power, particularly nuclear power accidents that dominate the discourse are largely radiophobic in nature. Indeed, news coverage relating to nuclear often makes direct references to the Chernobyl accident (Perko et al., 2019), priming the audience. This acts as a powerful anchor that exerts considerable influence on the relationship with radiation and nuclear power, especially in a (perceived) emergency setting. Acting in conjunction with the anchoring bias is the tendency to seek out, or otherwise interpret, information that confirms already-held views (Nickerson, 1998) –confirmation bias. There are abundant examples of this, but perhaps the clearest one is in relation to the Chernobyl accident and its health impacts, specifically the number of fatal cancers potentially caused by the accident. Whereas the official death toll currently stands at 54 (UNSCEAR, 2008) – including the firefighters that succumbed to Acute Radiation Syndrome after receiving fatal doses during the first hours of the accident – it is commonly perceived that the accident had a considerably higher death toll. Indeed, this is a recurring narrative which relies on various reports (Greenpeace, 2006; Yablokov et al., 2010) that has estimated fatal cancer cases between 93,000–985,000. These reports often rely on a widely discredited application of collective dose for calculating potential health impacts – multiplying many, often extremely low, individual doses with large populations to calculate a theoretical detriment. The International Commission on Radiological Protection (ICRP) states that *"[c]ollective effective dose is not intended as a tool for epidemiological risk assessment, and it is inappropriate to use it in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided"* (ICRP 2007, 2007). Despite such methodological issues, these reports often receive considerable attention, especially in the media (BBC, 2006; Financial Times, 2006; Vidal, 2011; Blomgren, 2011). With widespread radiophobic tendencies within the general public, news coverage mentioning such high death tolls, in conjunction with both confirmation bias and anchoring bias, act as powerful reinforcers of radiophobia. Indeed, some of the events during the 2022 Russo-Ukrainian war are clear examples of how this discourse exerts considerable influence on the way nuclear-related news are reported. When the conflict reached nuclear power plants in Ukraine (Chernobyl and Zaporizhzhya), the media portrayal of the purported risks where alarmist in nature, often making references to doomsday scenarios (Guillot, 2022; de Ferrer, 2022; Jacobo, 2022; Branigin et al., 2022; NBC News, 2022; Patel-Carstairs and Sephton, 2022; Feinberg, 2022) with little scientific accuracy. Such reporting was also aided by the clearly radiophobic language deployed by e.g. Ukrainian president Volodymyr Zelensky, who on 4th March told the media *"[i]f there is an explosion [at the Zaporizhzhya nuclear power plant], that's the end of everything. The end of Europe. This means the evacuation of Europe … Do not allow Europe to die from a catastrophe at the nuclear power plant"* (Zelensky, 2022).

Beyond these psychological factors, the nuclear community's communication efforts have acted as a significant driver of radiophobia, especially in ensuring its continuous existence. Indeed, since the mid-1960s, a cornerstone in the industry's communications strategy has, de facto, been driven by radiophobia: focusing on the safety of nuclear power. This arose out of increased public concerns about the potential health effects of radiation, which had been heightened by the fallout from atmospheric testing of nuclear weapons which, subsequently increased anxieties towards nuclear power. However, by centring its communications efforts on safety aspects, a psychological process – the so-called boomerang effect – has likely been triggered amongst the general public, acting to both entrench and reinforce radiophobia. The boomerang effect, which is defined as *"a situation in which a persuasive message produces attitude change in the direction opposite to that intended"* (American Psychological Association, 2021a), can be clearly seen when adopting a longitudinal angle. Indeed, despite considerable efforts by the nuclear community over many decades to lessen anxieties about safety, it remains one of the chief concerns and objections raised in relation to nuclear power worldwide. This, opposite effect to that intended meets the criterion of the boomerang effect (Byrne and Sol Hart, 2016). The underlying process is simple: by communicating about nuclear safety (especially when unprompted), the audience is primed to consider issues relating to nuclear power accidents and the impacts of radiation exposure. It not only triggers the pre-existing anchor for these issues, but also activates the affective pool of imagery and subsequently triggering an often negative, radiophobic, response, which is the unintended consequence. By focusing its communications on safety for decades, the nuclear community has ensured that the anxieties about nuclear energy are not far from people's minds, safeguarding the continuous existence of radiophobia.

Given the range of different socio-psychological processes that has been outlined above, when returning to one of the aforementioned clinical criteria for a phobia – fear being out of proportion with its sociocultural context radiophobia must be considered as being proportionate. This marks a significant departure from the existing conceptualisation of radiophobia, rejecting the notion of irrationality.

5. What are the consequences of radiophobia?

Perception matters, and it can drive behaviours that have detrimental consequences. This is the case with radiophobia; indeed, one of the main contexts for the term is to describe the sociopsychological and economic effects (e.g. value of goods from an affected region dropping due to perceived contamination (Pastel, 2004) or consumer avoidance of particular foodstuffs (Miyata and Wakamatsu, 2018)) that have been

observed following major radiological events, such as Hiroshima, Nagasaki, Chernobyl, Goiania, and Fukushima Daiichi. In many of these cases, affected populations have experienced severe stigmatisation (and self-stigmatisation) due to perceived contamination or "impurity", resulting in discrimination against these populations, and a range of negative health effects that are the result of radiophobia, rather than radiation exposure (Lifton, 1968; Yevelson et al., 1997; Slovic, 2012).

The first example of the consequences of radiophobia at a major scale comes from Japan. The survivors of the atomic bombings of Hiroshima and Nagasaki in August 1945 were designated as *Hibakusha*, which translates to *"person affected by exposure [to radiation]"*. Approximately 650,000 people have been designated as *Hibakusha* by the Japanese government. A significant proportion of the survivors of the bombings were found to suffer from various mental health issues (Shinfuku et al., 2009), and whilst the trauma of the bombings has a negative mental health impact, studies have found that anxieties about health effects and stigmatisation have a more significant impact in terms of mental health (Nozomu et al., 2012). Indeed, these individuals have been subjected to significant stigmatisation and discrimination as a direct result of their perceived radiation contamination, something that ensues to this day. This has included being denied access to public spaces, employment opportunities, and being considered unsuitable for marriage (Atomic Heritage Foundation, 2017), which was fuelled by incorrect assertions that exposed individuals or their descendants would be radioactive or carry significant genetic defects as a result of their exposure. However, there is no evidence to suggest an increase in congenital malformations or birth defects in children born to *Hibakusha* parents (Ozasa et al., 2019). The potency of Hiroshima and Nagasaki in shaping the early days of radiation discourse is clear, as well as lends its consequences lending themselves to the conclusion that radiophobia is not uniquely associated with nuclear power, unlike statements to the contrary (Grimston, 2020).

Nevertheless, radiophobia is predominantly associated with nuclear power accidents. Following such accidents, evacuees often showcase significantly elevated levels of depression and anxiety (Havenaar et al., 1997; Brumfiel, 2013; Maeda and Oe, 2017; Tsujiuchi et al., 2016; Shigemura et al., 2021). Following Chernobyl, anxiety and stress levels were found to be 100% above controls, with the self-reporting of health issues three to four times higher than controls (The Chernobyl Forum, 2006). However, diagnoses of mental health conditions have not increased during the same timeframe, pointing clearly towards a stress response amongst the population, stemming from the effects of evacuation and (perceived) radiation exposure, as well as feelings of helplessness and overall fatalism (Havenaar et al., 2005; Morrey and Allen, 1996). Indeed, the Chernobyl Forum found that *"… the impact of Chernobyl on mental health is the largest public health problem unleashed by the accident to date"* (The Chernobyl Forum, 2006). A very similar picture emerged following the Fukushima Daiichi, where evacuees were found to have elevated levels of mental health problems, alcoholism, and PTSD (Suzuki et al., 2015; Maeda et al., 2018; Ropeik, 2016). It was found that 15% of all adults suffered from extreme stress, five times above the expected rate, and stress levels amongst children being 100% above average (Brumfiel, 2013). Stigmatisation of the evacuated population has been reported, being expressed through e.g. bullying (Sawano et al., 2018), as well as increased substance use (Terayama et al., 2020). Evidence also suggests that suicide rates are significantly elevated in Fukushima prefecture, especially amongst those above 50 years of age (Takebayashi et al., 2020).

Additionally, with radiation exposure being perceived to pose a considerable congenital and hereditary risk - irrespective of dose or dose-rate - there were an observed increase in elective abortions following Chernobyl. Some doctors even recommended abortions, even if there was no evidence supporting such a recommendation (Bromet et al., 2002). Indeed, there is no evidence of heritable effects due to irradiation of parental germ cells (Otake et al., 1990; Schull et al., 1966; Neel et al., 1988, 1990; Kodaira et al., 2010; Izumi et al., 2003; Kamiya et al., 2015; McLean et al., 2017). Equally, any malformation following in utero exposure would only occur above dose thresholds above those seen following nuclear accidents (The Chernobyl Forum 2006 Chernobyl, 2006; Little, 1993; Castronovo, 1999). Due to methodological issues and uncertainties, it is impossible to ascertain with complete certainty the number of abortions resulting from radiophobia. Nevertheless, it is clear that abortions did increase in Denmark (Knudsen, 1991), Italy (Spinelli and Osborn, 1991), Greece (Trichopoulos et al., 1987) and Finland (Auvinen et al., 2001). However, this phenomenon was not seen in all parts of Europe – for instance, there was no statistical increase in abortions in e.g. Sweden (Odlind and Ericson, 1991), Norway (Irgens et al., 1991) or Hungary (Czeizel, 1991). The perceived congenital risks – which acts a powerful fuel for radiophobia – has also had negative consequences on those who were evacuated from Chernobyl as infants (or whose mothers were evacuated whilst pregnant) self-rated their health as more negative than their non-Chernobyl peers, even though there were no actual health differences (Bromet et al., 2009). This discrepancy was linked with health risk perceptions, which inevitably is directly connected with radiophobia. This discrepancy does, however, manifest in other guises and outside of the nuclear power or nuclear weapons context.

In 1987, merely a year following Chernobyl, the next incidence of significant radiophobia occurred, this time in Goiania, Brazil. Following the theft of a disused medical source, radioactive cesium-137 was spread within a small community in the city. The ensuing radiation exposure resulted in 25 people needing hospital care, of which four subsequently died. Traces of the cesium could be found Goiania which caused considerable anxiety, and signs of radiophobia was abundant. During the early weeks of October, 3–4000 people reported to screening points in the city, with more than 112,000 people eventually having been screened for radiation contamination, with only 249 individuals with at least nominal levels of contamination. This screening was, however, not driven by medical justification, but rather by fear. Furthermore, more than 8000 individuals requested certificates that declared them free from contamination, but discrimination was nevertheless abundant, with hotels refusing guests from the city, and both pilots and bus drivers denying the boarding of passengers from Goiania (Vinhas, 2003). However, radiophobia had more widespread consequences following the incident. For instance, it caused a clear decrease in hotel bookings, and conferences being cancelled in the city as a response to radiophobia. Furthermore, the wholesale value of agricultural produce from the state that Goiania is located in dropped by 50% as consumers feared contamination, with sales of produce and cattle decreasing by more than 20% (Vinhas, 2003; Kasperson and Kasperson, 1996). Overall GDP for the Goias State fell by more than 15% as a result of the radiophobic response incident, taking more than five years to recover (Vinhas, 2003). A very similar picture can be seen following the Fukushima Daiichi accident, with stigmatisation of agricultural produce creating economic hardship due to radiophobia (Miyata and Wakamatsu, 2018; Tsuyoshi, 2021). The consequences of radiophobia do, however, extend beyond those that have experienced an incident or accident involving radiation. This includes hesitancy towards - or outright rejection of - nuclear technologies. This can have considerable negative impacts as these technologies can be used for a number of different beneficial applications (Bilbao y Leon and Lindberg, 2022), ranging from the mitigation of climate change (Brook, 2012; Baek and Pride, 2014; Hong et al., 2015; Liddle and Sadorsky, 2017; MIT Energy Initative, 2018; OECD-NEA, 2012; OECD-NEA, 2019; International Energy Agency, 2019) and air pollution (Severini, 2017; Kharecha and Hansen, 2013) through the use of nuclear power, to food sterilisation (Verma and Gautam, 2015; Thayer, 1993; World Health Organization, 1994; World Health Organization in collaboration with the Food and Agriculture Organization, 1988; U.S. Food and Drug Administration, 2018; International Atomic Energy Agency, 2021), the prevention of various zoonotic diseases (Klassen et al., 2021a, 2021b; Klassen, 2009), and nuclear medicine (Bilbao y Leon and Lindberg, 2022; Jaffray et al., 2015). In many settings, this hesitancy already exist towards many of the aforementioned

technologies, despite their safety having been demonstrated. One clear example of radiophobia directly impacting policymaking, and creating other risks as a result, was the German decision to phase out its nuclear power fleet following Fukushima Daiichi. This decision has seen greenhouse gas and air pollution emissions increase due to an increased use of various fossil fuels (including lignite) (Jarvis et al., 2019) and thus exacerbating the risks posed by climate change. It is estimated that the social cost to Germany as a result of moving from nuclear to coal stands at approximately 12 billion EUR annually, largely driven by the negative health effects caused by air pollution (Jarvis et al., 2019). A similar picture emerged in Japan, which following the same accident took its entire nuclear fleet offline for safety checks and a reappraisal of the country's energy policy. As a result of this, driven primarily by a radiophobic reaction to the accident, Japan's dependence on fossil fuels increased, with an associated rise in emissions of both greenhouse gases and air pollution (Kharecha and Sato, 2019).

This multitude of examples of the impacts of radiophobia, covering a broad range of both public health, economic and environmental, highlights the very diverse nature of the consequences that radiophobia has had. At this point, it would be pertinent to explore the driving forces that underpin the phenomenon.

6. Is there a constructive future for radiophobia?

Radiophobia is an important concept that can play a major role in trying to better understand humantiy's relationship with radiation but, as highlighted, it has a troubled past. It is clear that it has been a contentious term for most of its modern existence, often used as a device attempting to invalidate public concerns about the public health risks associated with radiation, especially from nuclear power plants. This is well-documented throughout the history of the nuclear debate (Hamblin, 2012), and there can be little doubt that this played an important role in shaping the strongly polarised nature that the nuclear conversation exhibits today. Indeed, the use of 'radiophobia' in this context has most likely played a major role in causing the negative sociopsychological and economic effects seen following radiological incidents. Furthermore, there is no evidence to suggest that the way the public responded following such incidents in any way were anomalies, strongly suggesting that radiophobic responses should be expected at future nuclear or radiological incidents. The nuclear industry's response has been to disseminate more information about radiation in an effort to normalise radiation. Coates (2014) summarises it well, stating that the nuclear industry's mantra is based on the notion that *"tell them the facts and they will love nuclear power"* (Coates, 2014). Indeed, a commonly voiced opinion within the nuclear industry is the notion that *"[a] low level of public acceptance of nuclear power is usually due to a lack of knowledge"* (World Nuclear News, 2020) and that *"… incorrect information from the media made people afraid of nuclear energy"* (World Nuclear News, 2019). Following Fukushima, leaders of the industry vowed to *"… step up our efforts* ***to educate the public****, not only about what happened at Fukushima, but* ***also about basic facts*** *regarding nuclear energy [authors' emphasis]"* (Candris, 2019). However, despite efforts by the nuclear community – which predates the accident at Fukushima Daiichi – to attempt to win favour with the public by various information campaigns, there is little evidence to suggest that these efforts have paid off. Indeed, the nuclear community's general tendency towards adhering to the knowledge deficit model – *"the assumption that ignorance is the basis of a lack of societal* support *for various issues in science and technology"* (https://journals.sagepub.com/doi/abs/10.1177/0963662516629749, 1177) – runs directly counter to the aforementioned processes that shape human thought and decision making, and renders most communication efforts ineffective, as facts are poorly suited to displace deeply held emotions and imagery. This failure can largely be traced back to the same philosophical commitment around public "irrationality" that is associated with radiophobia, exposing a deep schism between parts of the nuclear community on the one hand, and the general public on the other. This schism is driven by deeply contrasting views, as stated by Flynn et al. (2003), highlighting a clear *"… contrast between the public's stigmatisation of nuclear power, a widely held belief that certain nuclear technologies are inherently dangerous, unwise, unnatural, and even immoral, and the position of nuclear proponents who envision nuclear technologies as right, necessary, and inevitable because they are based on deep scientific and natural truths"* (Flynn et al., 2003). These views have fuelled parts of the nuclear community's assumption of radiophobia being a symptom of "irrationality" on the part of the public. Unless addressed through effective communication practices that significantly departs from the status quo, radiophobia will continue to cause detrimental consequences, and exacerbating any future radiological accident (Gauntlett et al., 2019). This is imperative for as long as radiation will be used; indeed, accidents are inherent to humanity and history tells us that even if nuclear accidents are incredibly rare, it is prudent to assume that further accidents are likely to occur. Historical incidents involving radiation have showcased that the radiological consequences are several orders of magnitude smaller than originally feared, but also highlighting the tragic consequences of radiophobia. This makes addressing radiophobia urgent as any efforts trying to decrease it must take place before any perceived or actual nuclear incident or accident (Lindberg, 2021b), which includes contextualizing radiation risks and placing them in due perspective.

Indeed, because of its considerable impacts and the very likely continued use of radiation for beneficial purposes, radiophobia as a term has a crucial role to play as little suggests that the extreme perception towards radiation is dissipating. However, in order for radiophobia to have a constructive future, it is crucial that the notion of radiophobia being an "irrational" fear is abandoned. Failing to do so, radiophobia will continue to act as an ostracising rhetorical device that fails to address the underlying issue that ultimately, as noted, causes considerable harm. The nuclear community might not have created radiophobia, but they have played a pivotal role in ensuring its continuing survival. This has largely been driven by decades of adherence to communication practices – underpinned by the knowledge deficit model – that has centred on safety. Furthermore, the radiation protection community has a significant responsibility in ensuring that radiophobia is not reinforced by placing radiation risks due context and perspective, and communicating this in an appropriate manner (Lindberg, 2021a), something that has not always happened. However, as mentioned earlier, this has only acted to entrench radiophobia in public discourse. Two crucial steps must be taken immediately to start to address this. Firstly, the nuclear community must recognise the processes that underpins radiophobia and how any radiophobic response must be considered proportionate to the current sociocultural context that radiation is shaped by. Secondly, the way radiation is communicated about must be fundamentally reformed. This is contingent upon the abandonment of the knowledge deficit model. Whilst the provision of facts might play a role in shaping perceptions, it would be a minor effect, if at all found (Slovic, 1999; Sundstrom et al., 1977; Clelland and Bremseth, 1977; Davidson and Freudenburg, 1996; Wang et al., 2020). Indeed, as noted earlier, confirmation bias will likely render any facts-centric communication strategies largely ineffective. This is, in turn, further exacerbated by the fact the last few decades have seen a sharp decline in public trust across the world, with most professions and institutions seeing trust levels eroding (Löfstedt, 2004; Löfstedt, 2009; Edelman, 2020). Operating a facts-centric strategy to combat radiophobia in a post-trust (and, as some have argued, post-truth (McIntyre, 2018)) environment is largely futile, as the public reverts back to a high level of adherence of pre-existing biases and heuristics, with studies finding that prior knowledge exerting considerable influence (Perko et al., 2013, 2014; Visschers and Wallquist, 2013). This is also where radiophobia has to be addressed, as its lends itself to many such heuristics, which human perception and decision-making largely depends on. The new communications paradigm replacing the status quo must seek to create new affective imagery, taking into account the many

heuristics and biases that play a central role in shaping perceptions. In addition, the perceived risks and benefits of radiation and nuclear technologies linked to the affective marker it is associated with. This highlights those judgments are, at least partially, shaped by how the public feel about the activity at hand. Indeed, it has been found that positive feelings towards an activity resulted in risks being judged as low and benefits high, and vice versa (Alhakami and Slovic, 1994; Finucane et al., 2000). This means that any communications strategy should stress the benefits of the technologies which, in turn, should be supported by (positive) affective imagery. Replacing the imagery that radiation has become intimately associated with will take time and significant efforts, as during the last seven decades radiophobic discourse has largely been allowed free rein. Whilst climate change has, prima facie, given nuclear power a new lease on life, it is far from certain that it will yield the changes required in terms of imagery to revert radiophobia. Indeed, some studies have found that the nuclear power-climate change coupling results in "reluctant acceptance", with nuclear power only being embraced as a matter of last resort (Corner et al., 2011; Bickerstaff et al., 2008; Pidgeon et al., 2008; Venables et al., 2009; Keller et al., 2012). This would hardly be a sustainable support base, and the imagery of climate change would do little in terms of providing positive imagery to replace the radiophobic ones. It is also evident that this replacement process would not be achieved in one go, but rather incrementally. With the ongoing surge in energy prices (especially in Europe) and the question around security of supply that the Russo-Ukrainian war have exacerbated, a window of opportunity for imagery replacement has opened up. Historically, there is a close link between energy security concerns and support for nuclear power (Gupta et al., 2019), suggesting that this could provide a fertile environment for affective imagery to be created.

With radiophobia undermining the long-term sustainability of nuclear technologies, and with its severe consequences following nuclear or radiological incidents or accidents, lessening radiophobia should be considered of the utmost importance. Doing so will require a paradigm shift in how radiation and its different applications are being communicated about. Equally importantly, the conceptualisation of radiophobia itself needs to change, away from it being an "irrational" fear that facts can "cure", towards being a phenomenon grounded in social psychology. This paper has provided a starting point for this paradigm shift, but it is clear that further efforts will be required.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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