The social acceptance of fusion: Critically examining public perceptions of uranium-based fuel storage for nuclear fusion in Europe

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CRJ led the design and distribution of the questionnaire-based survey and the analysis and reporting of the findings. SM and SY assisted in the design and distribution of the survey.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. We thank Barry Butler (CCFE) for his assistance in revising earlier versions of this article.

Abstract

The public acceptability of emerging industrial technologies can affect their chances of commercial success. In large, demographically diverse samples from the United Kingdom (*N* = 438) and Germany (*N* = 390), we show for the first time the stigmatizing impact that the proposed use of depleted uranium (DU) as a tritium fuel storage option for nuclear *fusion* has upon public attitudes towards nuclear *fusion*. Participants' attitudes towards nuclear fusion in both cohorts were assessed at four time points within an online questionnaire-based survey: pre-information about nuclear fusion (Time 1); post-information about fusion (Time 2); pre-information about DU (Time 3); and post-information about DU (Time 4). Attitudes towards nuclear fusion were generally more positive in the UK; however, both the UK and German cohorts showed a similar 'flip-flop' pattern in opinions over time. Specifically, an initial improvement in attitudes (Time 1 – Time 2), which was taken as evidence of the value of delineating nuclear *fusion* from nuclear *fission*, was followed by a significant downturn (Time 2 – Time 3) upon the announcement that DU would be involved in fuel-storage. This downturn in attitudes was tied to participants' initial negative cognitive and affective evaluations of DU. The stigmatizing impact was found to partially reverse (Time 3 – Time 4) following the provision of information about the nature and purpose of DU within *fusion*. The study findings have clear implications for public engagement and communication efforts relating to current and future nuclear *fusion* demonstration projects.

1 Background

The public and broader social acceptability of emerging industrial technologies can affect their chances of commercial success or failure.[1] For instance, by lobbying politicians, publics can influence the decisions made about technologies at a strategic/national level. Similarly, by engaging in forms of supportive or oppositional protest, publics can affect the ease with which facilities are deployed at regional or local levels. There are a growing number of instances where problems or failures within public engagement and deliberation have led, in part, to delays or curtailments to the introduction of new technologies at both national (e.g. *genetically modified agriculture*) and local levels (e.g. *renewable energy technologies*).[2–5] This raises the importance of engaging publics with technological innovation in order to learn more about the nature and antecedents of their attitudes.[1,6,7]

Consistent with this, efforts to understand the nature and antecedents of public attitudes and perceptions of emerging technologies is increasingly considered to be a key component of the research, development, demonstration and deployment process. There are also growing calls for earlier and more participatory involvement of publics in the development cycle of these technologies.[8,9] This is seen as particularly important within Westernised democracies where policy and institutional change often requires the support of affected individuals and communities.[6]

The current article reports on the findings of a questionnaire-based survey study, conducted in the UK and Germany. This survey was designed to assess lay-public responses to the planned use of depleted uranium (DU) beds as a means of tritium storage for use in nuclear *fusion* reactors. While DU beds are a mature and reliable technology, questions remain as to how their intended use might affect public approval of nuclear *fusion*.

1.1 The proposed roadmap for commercial-scale nuclear fusion power generation

Nuclear *fusion* is being developed as a prospective means of generating a carbon- and combustion-free source of energy for use in electric power generation.[10] For proponents of the technology, nuclear *fusion* is seen as a potentially important part of the future energy mix; allowing us to safely and securely meet growing demand for electricity in a carbon-constrained world.[11,12] At present, research into nuclear *fusion* remains at the experimental stage; however, there are ongoing international efforts to research, develop and demonstrate the technical and commercial feasibility of the technology.[13]

A key roadmap for the advancement of nuclear *fusion* – curated by *EUROfusion*[14] – begins with the experiments currently being conducted at the Joint European Torus (JET) facility in the UK. The results of these experiments are helping to inform the design and operation of ITER, which stands to be the world's largest and most advanced experimental *fusion* reactor.[15] ITER is under construction in the south of France and is scheduled to become operational in December 2025. ITER is a joint collaboration between 35 nations (including the European Union, China, Russia, Japan, Korea, India and the US) and, when complete, is anticipated to be the first magnetic confinement device to produce net surplus energy during operation. Specifically, the power output from ITER should by ten times more than the external heating power injected into the reactor to sustain the reactions (i.e. 50 MW). Indeed, ITER should generate 500MW of *fusion* power and has been designed with the broad aim of demonstrating the technologies, materials and physics needed for commercial *fusion* power generation – including the 'breeding' (i.e. creation) of tritium fuel – which will be essential for the future roll-out of nuclear *fusion* power plant. Ultimately, learning from ITER is anticipated to form the foundations of DEMO.[16,17] If constructed, DEMO should, in principle, be a functioning demonstration power plant capable of supplying electricity to the grid. DEMO is anticipated to be the final step between ITER and a commercial *fusion* power plant and is due to come online around 2050.

EUROfusion recognises the integral role that the opinions of the pubic (and other key stakeholders) will play in shaping the path to the development of a commercial-scale nuclear *fusion* power plant. Congruently, there is an active social and economic studies team seeking to advance understanding of the roots of acceptance (or rejection) of nuclear *fusion* at socio-political and local levels.[14]

1.2 Public perceptions of nuclear fusion and the stigmatizing effect of language

The existing literature on public perceptions and attitudes towards nuclear *fusion* has begun to reveal much about their nature and antecedents, as well as the discourses used by lay-publics to think about the technology.[18–21] For instance, scepticism about the viability and relevance of *fusion* technology is commonplace due to the reported (and perennially distant) timescales to commercial operation. One of the key findings arising from this existing research has been the discovery of the negative 'branding' influence that the use of the term 'nuclear' can have upon opinions of *fusion*. In short, the nuclear label has been found to be associated with powerful and detailed collection of ideas and images (e.g. relating to catastrophic nuclear *fission* disasters like Chernobyl and Fukushima, as well as concerns about nuclear proliferation and nuclear war) which can serve to tarnish the things that the term is affiliated with.[19] Indeed, the potential stigmatizing influence of the term 'nuclear' is thought to have been so pervasive and fear-inducing so as to lead to the decision to drop it from the name (nuclear) Magnetic Resonance Imaging (MRI) – a form of medical imaging technology.[22]

The potential for stigmatization of nuclear *fusion* arising from such branding resonates with social psychological concepts relating to human judgement and decision-making such as the 'affect heuristic', the 'risk as feelings' hypothesis and other models of judgement that distinguish experiential and more analytic reasoning.[23,24] All of these point to the prominent role that affect ('gut' emotional reactions) can play in driving perceptions of the risks, costs, benefits and acceptability of unfamiliar hazards.[24] Indeed, research indicates that where people possess little knowledge of a given topic or hazard, they will often rely upon their experiential or ‘hot’ (i.e. affective) system to evaluate it as opposed to their analytic or ‘cold’ (i.e. cognitive) system.[23,25,26]

With this in mind, it is perhaps unsurprising that a person’s attitudinal and behavioural responses to unfamiliar topics or hazards can often hinge upon how they are framed (e.g. the terminology or narrative that is used to describe them).[27–30] Indeed, the nomenclature associated with technological innovation can and does shape how such innovation is perceived and responded to by publics.[31–33] For instance, in the context of energy technologies, Cacciatore et al.[33] investigated citizen acceptance of biologically derived fuels and found that participants responded more favourably to the term ‘biofuels’ than ‘ethanol’. It was suggested that this difference might have stemmed from the more natural sounding ‘bio’ pre-fix associated with biofuels and/or the food-for-fuel criticism that was more readily associated with the term ‘ethanol’ among their sample. Similarly, in a study by Clarke et al.[31] concerning citizen perceptions of unconventional hydrocarbon extraction, participants demonstrated a preference for the term ‘shale gas and oil development’ over ‘fracking’ (despite these referring to the same thing); the former being associated with more positive associations and impacts, and the latter associated with more negative ‘top-of-mind’ connotations.

1.2.1 Could the use of depleted uranium stigmatize public perceptions of nuclear fusion?

A root of the stigma that can be associated with the term nuclear is its links to fears about radiation and radioactivity. For instance, in the context of current nuclear power generation, the most common *fission* reactors in commercial operation (i.e. Pressurised Light Water Reactors and Boiling Water Reactors) use *enriched uranium* to drive the fission reaction and generate power. *Enriched uranium* is a form of uranium that has been industrially processed to contain a higher proportion of the fissile uranium-235 isotope. Less commercially-prevalent reactor types (e.g. Pressurized Heavy Water Reactors) while not reliant on *enriched* *uranium* as a primary fuel source, also commonly still rely on uranium fuel, just in an unenriched form.[34] Crucially, a reliance on uranium (in either enriched on unenriched forms) to power most nuclear *fission* reactors creates a source of highly radioactive, long-lived legacy waste. Moreover, in the event of catastrophic failings in the cooling systems controlling the *fission* reaction, it can be associated with a heightened risk of nuclear 'meltdown' (i.e. damage to the reactor core by overheating). And while nuclear *fission* plant and waste-management protocols are designed to maximise operational and public safety[35], and while accidents are extremely rare, both the risk of meltdown and the production of legacy waste are known to be key issues for fostering public acceptance.[25,36,37]

Nuclear *fusion* does not use uranium as a fuel source but instead reacts two forms of hydrogen isotope (deuterium and tritium) at high temperatures to generate power.[38] As tritium is a radioactive isotope of hydrogen, though, it requires special handling. As part of the experimentation using the Joint European Torus (JET) facility, *fusion* researchers at the Culham Centre for Fusion Energy (CCFE) are trialling the use of a fuel storage option that utilises DU beds to store the radioactive tritium.[39–41] The CCFE is the UK's national laboratory for research into nuclear *fusion* and is home to the JET experimental test facility (a forerunner to ITER and DEMO).[42] DU beds are technically favoured for this purpose due to the material properties of DU, which allow for more efficient storage and retrieval of the tritium fuel than other available options (e.g. Zirconium Cobalt).[43]

Akin to the potential stigmatizing influence proffered by the use of the term 'nuclear' we hypothesise that the use of DU (so called as it is processed to contain less of the radioactive uranium-235 isotope than natural uranium) could stand to exert a similar branding influence on perceptions of *fusion* technology among members of the general population. If such a stigmatizing effect were to be observed, this could stand to compromise public support for nuclear *fusion* as a power generating option for the future. We argue that this stigmatizing influence could occur in a number of ways. For example, where people conflate *depleted* (lower radioactivity) and *enriched* (higher radioactivity) forms of uranium due to their shared nomenclature; where the term ‘depleted’ is deemed to communicate material weakness or deficiency; and/or where DU is associated with undesirable historical uses (e.g. the use of DU in munitions manufacture for armed conflicts like the Gulf War).[44]

1.3 Research objectives

The primary objective of the current research was thus to assess whether the proposed use of DU as a tritium fuel storage medium would have a stigmatizing effect on lay-public attitudes towards nuclear *fusion* within demographically diverse samples from the UK and Germany. For the reasons outlined above, it was hypothesised that the prospect of using DU would exert a significant, negative impact upon respondents’ attitudes (Hypothesis 1). A secondary aim of the study was to investigate whether or not the anticipated stigmatizing influence could be lessened by the provision of a small amount of information about the nature and purpose behind the proposed use of DU. While one should take care not to assume that the rejection of technologies is simply the product of a lack of the ‘correct’ knowledge about them[45,46], there is growing evidence of the benefits of efforts to educate and inform publics about unfamiliar technologies in order to promote understanding, counter misperceptions and encourage informed discussion about their use. [47,48] We hypothesised that the opportunity to inform people about the specific properties of DU (including efforts to delineate it from *enriched* uranium) and the rationale for its use, via the provision of information, should significantly reverse any stigmatizing impact initially observed (Hypothesis 2).

2 Methods

2.1 Participants and Recruitment

Participants were recruited via an online survey-platform provider (Qualtrics: www.qualtrics.com). Demographically representative (in terms of age, gender) samples of participants were targeted in each country using an online participant-panel function provided by the survey-platform provider. Respondents received a small financial reward in exchange for their participation.

Of the $N = 1157$ UK respondents that began the survey, $n = 719$ were removed for either failing to complete the survey, 'straight-lining' responses to key questions (i.e. Q27 and Q36), indicating that they would not provide their best answers and/or for being a non-national (i.e. UK) resident. This left a final UK sample of $N = 438$. Of the $N = 553$ German respondents beginning the survey, $n = 163$ were removed for one or more of the reasons stated above, leaving a final sample from Germany of $N = 390$. Note that we use the terms 'UK' and 'German' sample(s)/respondent(s) within this paper to refer to the samples recruited from the UK and Germany, respectively. Sampling was done, however, based upon the 'country of residence' of the participants at the time of the survey, as opposed to their stated 'nationality'.

UK vs. German cohort comparison

The UK and German respondents were statistically comparable in terms of their trust in science, $t\ (826) = 0.11, p = .917$; their environmental values, $t\ (818) = 0.88, p = .381$; and their concern with the personal and societal impacts of climate change, $t\ (791.73) = 1.71, p = .089$ and $t\ (826) = 0.58, p = .562$, respectively. The UK respondents were more concerned by the issue of energy security than the German sample, $t\ (819) = 7.05, p < .001$.

While the gender distribution in each cohort was statistically comparable, $\chi^2\ (3, N = 828) = 2.73, p = .435$ (with an approximately 50% split in male and female respondents), there were statistically significant differences on some of the other socio-demographic measures.

Distribution of home vs. foreign nationals: There was a slight overrepresentation of foreign nationals within the UK sample and slight underrepresentation within the German sample, $\chi^2\ (2, N = 793) = 6.06, p = .048$.

Education level: There was a higher than expected number of UK respondents studying for (or with) undergraduate degrees relative to the number having attained only a Secondary/High or Primary school education. These trends were reversed for the German sample, χ^2 (4, N = 828) = 28.61, $p < .001$.

Age: There was a higher than expected count in the older age categories (55 years and above) for the UK sample and a lower than expected count for these categories in the German sample. These relationships were reversed in many of the younger age categories (25–54 years), χ^2 (6, N = 828) = 19.25, $p = .004$.

Employment status: There were greater than expected numbers of German respondents in paid employment or education, with fewer than expected in retirement. These relationships were reversed in the UK sample, χ^2 (5, N = 828) = 22.28, $p < .001$.

Taken together, the modal UK respondent was slightly older and had received more formal education than the modal German respondent but was less likely to be paid forms of employment. These slight demographic differences should be considered when drawing conclusions from each of the statistical analyses. For the frequencies, proportions, means and standard deviations associated with these socio-demographic analyses, see Table 1.

[TABLE 1 ABOUT HERE]

2.2 Measures and Materials

We used a questionnaire-based survey (QBS) to establish: (a) the nature of lay-public attitudes towards nuclear *fusion*; and (b) to track how the proposed use of DU as a fuel-handling option might affect these attitudes. The survey was created in English and German and comprised nine sections (see Figure 1 and sections 1-9 below). Information provided to respondents within the survey was developed in collaboration with the CCFE. Respondents were made aware of the affiliation with the CCFE at the start of the survey and were provided with web-links where they could learn more about the organisation in the debrief statement accompanying the survey.

[FIGURE 1 ABOUT HERE]

1. *QBS introduction*

A short paragraph introduced the researchers and their affiliations, provided an ethical statement and outlined that the QBS was interested in respondents' initial impressions (including perceived advantages and disadvantages) of nuclear *fusion*. A brief distinction between nuclear *fission* and *fusion* was drawn and respondents were informed that no prior knowledge was required to complete the survey and that we were interested in their personal opinions based upon what they knew of currently understood at the time of completion.

2. *Section A: Demographics and initial opinions of nuclear fusion + Tracker Questions (Time 1)*

Section A recorded key demographic details of the respondents and their baseline awareness, attitudes and familiarity with nuclear *fusion*. The questions and response options of relevance to the current study are outlined Appendix A, Table A1. Section 1 also included questions to identify respondents that did not adhere to the inclusion criteria for the study (i.e. respondents not living in the UK or Germany at the time of the survey; and/or not agreeing to provide good quality responses to the survey questions).

Tracker Questions: A set of five tracker questions assessed people's attitudes towards nuclear fusion at four key points of the survey (outlined below). These questions (all accompanied by 5-point response scales) assessed respondents' affective response to nuclear *fusion*; how beneficial, risky and worthy of investment they perceived nuclear *fusion* to be; and whether they would be happy to have a facility constructed locally:

1. On a purely emotional level, how positive or negative do you feel about nuclear *fusion* technology (NFT)? (very negative - very positive)
2. If developed, how beneficial or unbeneficial do you think NFT could be? (very beneficial – very unbeneficial)

3. Generally speaking, how risky or safe do you think NFT is? (very risky – very safe)
4. How worthy or unworthy of investment do you view NFT as being? (very unworthy – very worthy)
5. How happy or unhappy would you be for a nuclear *fusion* power plant to be built near you? (very unhappy – very happy).

Scale analysis on these questions for each sample at each time-point (i.e. Time 1: pre-information about *fusion*; Time 2: post-information about *fusion*; Time 3: pre-information about DU; and Time 4: post-information about DU) revealed that they had good reliability (Cronbach's $\alpha \geq .86$). Responses to these questions were averaged to form a composite score (i.e. *attitude to nuclear fusion*) for each cohort at each time point.

3. *Provision of information about nuclear fusion*

Respondents received two short paragraphs of text and accompanying diagrams designed to show: (a) the key differences between nuclear *fission* and nuclear *fusion* and how they are used to generate power; and (b) outline the current roadmap for moving nuclear *fusion* from its present (i.e. Joint European Torus or JET) and future (i.e. ITER c.2025) experimental-testing phases, to full-scale commercial operation (i.e. DEMO c.2050). Respondents then received brief details of five key advantages (i.e. sustainable and abundant energy; no carbon dioxide and no high-activity or long-lived radioactive waste; no risk of nuclear meltdown; low operating costs) and five key disadvantages (i.e. impact on energy demand; radioactive fuel and low-level radioactive waste products; no full-scale electricity production expected until 2050; high start-up costs).

Finally, respondents were invited to evaluate the quality of the information they received on four qualitative dimensions (using 7-point scales; strongly agree - strongly disagree, plus DK). On average, respondents agreed (or somewhat agreed) that the information was understandable ($n = 827$, $Mean = 2.22$, $SD = 1.21$); balanced ($n = 821$, $Mean = 2.46$, $SD =$

1.15); of good quality (*n* = 824, *Mean* = 2.32, *SD* = 1.08); and sufficient for them to make an informed decision about nuclear *fusion* (*n* = 824, *Mean* = 2.83, *SD* = 1.39). See Supplementary Information for exact wording and diagrams in Appendix A.

4. Section B: Evaluations of nuclear fusion technology + Tracker Questions (Time 2)

Section B contained the second set of Tracker Questions. Section B also investigated the antecedents of respondents' opinions towards nuclear *fusion* (e.g. perceived advantages and disadvantages). The responses to these additional questions are not analysed further as they are not of focal interest to the current article.

5. Section C: Initial awareness of and attitudes towards depleted uranium + Tracker Questions (Time 3).

Respondents were asked about their awareness ("Before today, had you heard of depleted uranium?" Yes; No) and self-claimed knowledge ("How much would you say you know about depleted uranium?" Nothing – have not heard of it; Nothing - have only heard the name; A little; A fair amount; A lot) of DU.

To assess how affective responses to the term DU compared with other terms incorporating the word uranium (i.e. uranium; natural uranium; enriched uranium); respondents were asked to rate how uneasy or calm each of the terms made them feel (10-point scale of 1-10, extremely uneasy – extremely calm).

In order to investigate the antecedents of respondents' attitudes towards DU, participants were asked to respond to 16 statements describing the *positive use-value* of DU (5-items: e.g. "Has important industrial uses"); the *negative use-value* of DU (5-items: e.g. "Creates unwanted links between *fission* and *fusion* industries") and common *negative associations* with DU (4 items: e.g. "Has negative affiliations with nuclear weapons"). Two additional items assessed the *positive labelling potential* (i.e. "Sounds less hazardous than uranium") and *negative labelling potential* (i.e. "Sounds more hazardous than uranium") of

DU relative to uranium. A full list of these items is available in Table 4. Items were created based upon the findings of focus groups from a separate study conducted prior to the creating the survey.

Reliability analysis indicated that the items within each sub-scale had acceptable to good reliability for both countries (Cronbach's $\alpha \geq 0.77$) and so they were averaged to form composite variables of *positive use-value*, *negative use-value*, and *negative associations*. The *positive-labelling* and *negative-labelling potential* items (reverse coded) did not form a scale with acceptable reliability ($\alpha = .44$) and so were treated separately. The section ended with Tracker Questions (Time 3).

6. ***Provision of information about depleted uranium***

Respondents were provided with two short paragraphs and accompanying diagrams designed to outline: (a) the basic characteristics of DU (e.g. how it is a low-radioactivity form of uranium produced as a by-product of uranium enrichment); and (b) the nature of its use as a means of storing tritium within the current and future nuclear *fusion* demonstration projects. Respondents also received short statements outlining the advantages (e.g. it can be used to capture and store tritium at room temperatures in a fully reversible reaction) and disadvantages (e.g. that it is chemically toxic if touched, inhaled or ingested).

Respondents were again invited to evaluate the information provided (using 7-point scales; strongly agree - strongly disagree, plus DK) on the same qualitative dimensions as outlined above. On average, respondents agreed (or somewhat agreed) that the information was understandable (n = 823, *Mean* = 2.55, *SD* = 1.34); balanced (n = 815, *Mean* = 2.68, *SD* = 1.27); of good quality (n = 817, *Mean* = 2.57, *SD* = 1.19); and sufficient for them to make an informed decision about nuclear *fusion* (n = 813, *Mean* = 3.04, *SD* = 1.45). See Supplementary Information for exact wording and diagrams in Appendix A.

7. *Section D: Identifying change to opinions about depleted uranium + Tracker Questions (Time 4)*

In order to check whether the provision of information had changed respondents' opinions about DU, they were again invited to complete the 16 *positive use-value*, *negative use-value*, *negative association* and positive- and negative-labelling items. They then completed the final set of Tracker Questions (Time 4).

8. *Section E: Trust in Science, Biospheric Values, and Energy Security and Climate Change Concerns*

Respondents completed the 'Trust in Science and Scientists Inventory'.[49] This 21-item scale measures domain-general trust in science and scientists (e.g. "I trust in the work of scientists to make life better for people"). Responses are made on a 5-point scale (strongly disagree – strongly agree), with higher scores pertaining to greater trust. The internal reliability of the scale was excellent for both the German and UK sub-samples ($\alpha \geq .90$) and so the items were averaged into one composite measure of '*trust in science and scientists*'.

Biospheric values were assessed using a 4-item scale adapted from de Groot and Steg.[50] Respondents rated how important they viewed: (1) Preventing pollution: protecting natural resources; (2) Respecting the earth: harmony with other species; (3) Unity with nature: fitting into nature; and (4) Protecting the environment: preserving nature. Responses to these items were made on a 5-point scale (Not at all important – extremely important, plus DK). The internal reliability of the items was excellent for both sub-samples ($\alpha \geq .92$) and so the items were averaged into one composite measure of '*biospheric values*'.

Energy security concerns were assessed using a 6-item measure developed by Corner et al.[51] Respondents registered their concern (4-point scale: Not at all concerned – Very concerned, plus DK) about the future rationing of energy; affordability of energy; reliance on energy imports; threat of terrorist disruption to supply lines; potential for power cuts and depletion of fossil fuels. The scale had good internal consistency for both sub-samples ($\alpha \geq .82$) and so a composite measure of '*energy security*' was calculated.

Climate change concern was assessed with two items, one registering concern over the potential personal consequences and the other concern about possible societal consequences: "Considering any potential effects of climate change which there might be on *you personally* [*society in general*], how concerned, if at all, are you about climate change?" (4-point scale: Not at all concerned – Very concerned, plus DK).

9. Debrief

Respondents were debriefed as to the aims of the research and were provided with links to websites where they could learn more about the CCFE and nuclear *fusion* technology.

3 Results

All data were analysed using IBM SPSS Statistics 24.

3.1 Awareness and self-claimed knowledge of nuclear fusion and depleted uranium

A. Nuclear Fusion: Fisher's exact tests showed that German respondents claimed to hold greater awareness of nuclear *fusion* than UK respondents and were less likely to conflate nuclear *fusion* and nuclear *fission*. Congruently, independent samples *t*-tests revealed that German respondents had more self-claimed knowledge of nuclear *fusion* than did the UK respondents, despite both samples claiming to have only recently heard of nuclear *fusion*. See Table 2 for the data and statistical tests pertaining to these claims.

B. Depleted Uranium: Fisher's exact tests revealed that both samples had comparable self-reported awareness of DU, with around half the respondents in each sub-sample claiming to have heard of it. Both samples claimed to hold similarly low levels of knowledge of DU with most indicating that they had only heard of the term. See Table 2 for the data and statistical tests pertaining to these claims.

[TABLE 2 ABOUT HERE]

Taken together, the German respondents were subjectively more familiar and knowledgeable about nuclear *fusion* than the UK respondents upon commencing the survey. Both cohorts, however, demonstrated low and statistically comparable levels of awareness and knowledge of DU.

3.2 Uninformed evaluations of uranium terminology

To investigate the extent to which DU might be stigmatizing, we assessed respondents' uniformed evaluations of the term DU relative to other uranium-based terms (i.e. *uranium*, *natural uranium* and *enriched uranium*). In all instances evaluations of the terms were lower than the hypothetical scale midpoint (5.50) indicating a relative unease. For relevant means and standard deviations, see Table 3.

[TABLE 3 ABOUT HERE]

A 2 (Country: UK, Germany) x 4 (Term: Uranium, Natural Uranium, Enriched Uranium, Depleted Uranium) repeated-measures ANOVA with Greenhouse-Geisser correction ($\varepsilon = 0.95$) due to violation of Mauchley's test of sphericity (χ^2 (5) = .91, $p < .001$) was conducted to see if the terms were evaluated differently both within and between the UK and German sub-samples. Significant main effects of Term, F (2.84, 2344.64) = 100.07, $p < .001$, $\eta_p^2 = .11$, and Country, F (1, 826) = 5.41, $p = .020$, $\eta_p^2 = .01$, were qualified by a significant Term*Country interaction, F (3.84, 2344.64) = 12.64, $p < .001$, $\eta_p^2 = .02$.

Planned pairwise comparisons (with Bonferroni correction) using the term *uranium* as the comparison standard revealed that, across the whole sample: (a) the term *natural uranium* was associated with less unease (Mean Diff. = -.73, $p < .001$); (b) the term *enriched uranium* was associated with greater unease (Mean Diff. = .36, $p < .001$); and (c) DU caused equivalent unease (Mean Diff. = +.01, $p = 1.00$).

Follow-up independent samples *t*-tests confirmed that both cohorts were comparable in their evaluations of the terms *natural uranium* and DU. UK respondents were significantly less anxious about the terms *uranium* and *enriched uranium* (see Table 3 for the data and statistical analyses pertaining to these claims). These findings revealed that the term DU was a source of unease for respondents in both countries and so there was reason to suspect that the term should exert a negative influence on attitudes to nuclear *fusion* when associated with the technology.

3.3 Assessing the stigmatizing influence of depleted uranium

In order to investigate how participants' attitudes towards nuclear *fusion* had developed over the course of the survey, a 2 (Country: UK, Germany) x 4 (Time: Time 1, Time 2, Time 3, Time 4) repeated measures ANOVA with Greenhouse-Geisser correction ($\varepsilon = 0.75$, Mauchley's test: χ^2 (5) = .82, $p < .001$) was conducted using the composite mean responses to the *Tracker Questions* as the dependent variable.

As a result, it was possible to investigate: (a) how baseline attitudes (Time 1) evolved as a result of the provision of some basic information about *fusion* (Time 2); (b) the extent to which attitudes (Time 2) were then affected by the announcement that DU was being considered for fuel storage (Time 3); and (c) how the provision of information about DU then affected attitudes towards *fusion* (Time 4). For the relevant means associated with this analysis, see Figure 2.

Analysis of the within and between-subjects contrasts revealed significant main effects of Time, F (2.47, 2042.87) = 37.00, $p < .001$, $\eta_p^2 = .04$, and Country, F (1, 826) = 3.95, $p = .047$, $\eta_p^2 = .01$; however, the Time*Country interaction was not significant, F (2.47, 2042.87) = 1.50, $p = .218$, $\eta_p^2 = .01$. These main effects indicated that UK respondents were generally more positive towards nuclear *fusion* than German respondents and that there were significant variations in respondents' attitudes over time. The lack of a significant interaction, however, indicated that the trends in respondents' attitudes over time within each country were generally comparable.

[Figure 2 ABOUT HERE]

Pairwise comparisons (with Bonferroni correction) on the full-sample means (vs. Time 1) revealed that the information provided about nuclear *fusion* between Time 1 and Time 2 had a significant positive effect on attitudes (Mean Diff. = +0.18, $p < .001$). The news that DU was to be used in the tritium handling system (between Time 2 and Time 3) returned attitudes to their Time 1 (i.e. baseline) levels (Mean Diff. = +0.01, $p = 1.00$). While the provision of information about the nature and purpose of DU (between Time 3 and Time 4) did improve attitudes to nuclear *fusion* once again (Mean Diff. = +0.07, $p = .023$), they failed to recover to the levels seen before the use of DU was announced (Mean Diff. Time 4 vs. Time 2 = -0.11, $p < .001$).

A series of follow-up 2 (Country) x 2 (Time) repeated measures ANOVAs were used to assess how respondents' attitudes evolved during the survey: (a) Time 1 – Time 2; (b) Time 2 – Time 3; and (c) Time 3 – Time 4 (see Figure 2 for the inferential statistics). The results revealed that between Time 1 and Time 2 there were main effects of Time and Country but no significant interaction. Attitudes improved equivalently for both groups over time but UK respondents were significantly more favourable overall. Note that German respondents' attitudes started from a position of true ambivalence (Mean = 3.00; SD = 0.86) while UK respondents were generally favourable towards nuclear *fusion* (Mean = 3.14; SD = 0.85). Between Time 2 and Time 3 there was a main effect of Time only, with participants in both countries becoming less positive to nuclear *fusion*. Finally, between Time 3 and Time 4 there was a main effect of Time and a marginally significant interaction. Respondents became significantly more positive towards nuclear *fusion* over time, with this effect being marginally (although not significantly) stronger within the UK compared to Germany.

These analyses confirmed both our primary hypotheses: (1) that the term DU did appear to have a stigmatizing influence on attitudes towards nuclear *fusion*; and (2) that this stigmatizing influence could be somewhat (although not wholly) reversed by the provision of information about the nature and purpose of DU.

3.4 Explaining the stigmatizing influence of DU

Multiple linear regression (MLR) analysis (using pairwise deletion) was used to predict respondents' evaluations of nuclear *fusion* at Time 3 (i.e. where the stigmatizing effect of the proposed use of DU appeared to occur). Respondents' subjective evaluations of: (a) the *negative use-value*, (b) the *positive use-value*, (c) the *negative associations*; (d) the *negative labelling potential* of DU; and (e) the *positive labelling potential* of DU, *before* receiving information about the material were included as predictors.

Separate analyses were run for the UK and German cohorts. In both cases, assumptions for MLR were met although three outliers from the UK cohort and four from the German cohort were removed before analysis. The full results of the analysis can be seen in Table 4.

[TABLE 4 ABOUT HERE]

In the UK, the regression model explained 25.8% of the variance in respondents' attitudes, $R^2 adj. = .258$, $F\ (5, 385) = 28.17$, $p < .001$. Stronger evaluations of the benefits of using DU and weaker evaluations of the drawbacks of using DU were associated with more favourable attitudes. Further, the more that people believed that DU sounded hazardous the less favourable they were to nuclear *fusion*. In Germany, the model explained 32.9% of the variance in attitudes, $R^2 adj. = .329$, $F\ (5, 351) = 35.90$, $p < .001$. Stronger evaluations of the benefits of using DU were associated with more favourable attitudes, while the more that people felt that the term DU sounded hazardous the less favourable they were to nuclear *fusion*.

3.5 Assessing the influence of information provision on attitudes to depleted uranium

In order to help explain the partial positive rebound in attitudes to nuclear *fusion* between Time 3 and Time 4 (i.e. following the provision of information about DU), a series of 2 (Country: UK, Germany) x 2 (Time: Time 3, Time 4) mixed between-within subjects

ANOVAs were conducted. The dependent variables were respondents' evaluations of: (a) the *negative use-value*; (b) the *positive use-value*; (c) the *negative associations*; (d) *negative-labelling potential*; and (e) *positive labelling potential* of the material. For the means, standard deviations and statistical tests associated with the following claims, see Table 5.

[TABLE 5 ABOUT HERE]

Negative Use-Value: There was a significant main effect of Time and a non-significant Time*Country interaction. The between-subjects contrast for Country was not statistically significant. Respondents' concern with the *negative use-value* of DU reduced to a similar extent in both countries after receiving information about DU.

Positive Use-Value: There was a significant main effect of Time and a significant Time*Country interaction. The between-subjects contrast for Country was not significant. Respondents' evaluations of the *positive-use value* of DU improved over time, with this improvement being more pronounced in the UK.

Negative Associations: The main effect of Time was significant, as was the Time*Country interaction. The between-subjects contrast for Country was not significant. There was a reduction in the perceived *negative associations* connected to DU in both countries, with a more pronounced effect in the UK.

Negative Labelling: The main effect of Time was significant, as was the Time*Country interaction. The between subjects contrast for Country was not significant. Respondents' in both countries were less likely to view DU as being more hazardous than uranium after receiving information about DU. This effect was more pronounced in the UK.

Positive Labelling: The main effect of Time was significant, as was the Time*Country interaction. The between subjects contrast for Country was not significant. Respondents in both countries were more likely to see DU as less hazardous than uranium at Time 4. This effect was more pronounced in the UK.

4 Discussion

The results of this study provide first insight into the stigmatizing influence that the proposed use of DU within a planned tritium fuel storage option for nuclear *fusion* has upon public attitudes towards the technology. While less radioactive than natural and enriched forms of uranium, DU was discovered to evoke feelings of unease within both our UK and German samples. In the UK, this general unease was roughly equivalent to that yielded by the term *enriched uranium*, while in Germany evaluations of the term were less extreme but still negative. Congruently, and as predicted in Hypothesis 1, the proposed pairing of DU with nuclear *fusion* led to a significant downturn in respondents' evaluations of nuclear *fusion* (Time 2 to Time 3).

Further analysis revealed that respondents' attitudes towards nuclear *fusion* at Time 3 (having just heard about the proposed use of DU) were significantly predicted by a general sense that DU might be more hazardous than uranium (i.e. *negative labelling potential*). This relationship was particularly strong within the German sub-sample. In the UK only, the perceived risks with the use of DU (i.e. *negative use value*) were also linked to more negative attitudes to *fusion*. In both countries, evaluations of the *positive use value* of DU (i.e. the benefits of using DU) were linked to more favourable attitudes towards *fusion*. By contrast, respondents' awareness of the negative historical associations that DU shares with other sectors (e.g. armed conflict) were not predictive of attitudes towards *fusion* in either sub-sample.

While clearly evidencing that there is a stigmatizing effect of the proposed use of DU for nuclear *fusion*, we argue that future research should seek to learn more about the specifics of the branding influence. For example, in the UK it is possible that the root cause of the branding effect was due to participants conflating *enriched* and *depleted* uranium. Both terms were associated with comparable unease, which could be taken as evidence that participants were confusing the terms. Another possibility is that participants believed that the term ‘depleted’ communicated something negative about DU (e.g. that it was deficient or weak), leading to more specific and defined objection on these grounds. Interestingly, there was greater separation of *enriched* and *depleted* uranium within Germany, suggesting that participants saw the materials (or the terms at least) to be qualitatively distinct. Thus, we argue that an initial step in any follow-up research should be to learn more about the automatic cognitive and affective associations people draw with the term DU and the extent to which these are distinct from or comparable with those derived from the term *enriched uranium*.[26]

Crucially, beyond identifying the presence of a stigmatizing impact of the proposed use of DU on attitudes to nuclear *fusion*, the results also reveal how information about the material properties of DU was sufficient to prompt a partial rebound in attitudes towards a position of greater favourability. Indeed, the small amount of information provided to participants about DU apparently led to changes in the extent to which respondents classed the substance as hazardous (relative to uranium *per se*), as well fostering increases in the perceived *positive use value* and decreases in the *negative use value* of the material. These findings are consistent with those of other research that speak to the benefits of countering misperceptions and promoting informed public debate about technological innovation through education and outreach.[47,52] This is exemplified, for example, by recent attempts to engage publics in informed discussions about carbon capture and storage (CCS) and is more generally consistent with current shifts towards more participatory-involvement from publics (and other stakeholder) in decision-making relating to science and technological innovation.[47,48,53–55] While this rebound effect was observable in both the UK and German cohorts, however, a couple of things are noteworthy. First, in both samples the rebound was only partial and second, the rebound was more pronounced within the UK subsample.

The incomplete nature of the rebound in attitudes is a warning against assuming that attitudes towards innovative technologies, like nuclear *fusion*, are simply a product of one’s *objective* knowledge about the technology.[45,46,56,57] In this ‘knowledge deficit’ scenario, one should have perhaps anticipated a fuller rebound in attitudes to nuclear *fusion* following the provision of information about DU. Rather, attitudes towards science and technological innovation (like other topics) are shaped by manifold factors (e.g. trust, values, perceived norms, etc.) that also need to be accounted for.[58,59] Thus, while the observed rebound in attitudes to nuclear *fusion* could have been the product of respondents learning more about DU (e.g. delineating it from *enriched* uranium), its partial nature could relate to residual (or raised) concerns that followed the provision of the information. For example, for some the necessary ties between nuclear *fission* and nuclear *fusion* resulting from the use of DU (as DU is a by-product of uranium enrichment) would have been inconsistent with their desires for future denuclearisation and, hence, negatively evaluated.

The more pronounced rebound in attitudes among the UK cohort, relative to the German cohort, arguably reflects qualitative differences in respondents’ attitudes within each group. According to our survey, the German cohort was not only less favourable to nuclear *fusion* from the outset but also claimed to have greater knowledge of nuclear *fusion* than the UK cohort. This combination of less favourable attitudes and greater attitude certainty, likely explains the reduced rebound in attitudes between Time 3 and Time 4. Stronger attitudes are commonly less malleable than weaker attitudes but also, by being more certain of their attitudes to nuclear *fusion*, the German respondents might have had more motivation to critique or question the clarifying information about DU they were receiving.[60,61]

Finally, we argue that the greater scepticism with nuclear *fusion* registered by the German cohort throughout the study could relate to the nature of current energy policies within the UK and Germany. The UK has a pro-nuclear *fission* energy policy, whereas Germany is phasing-out nuclear *fission* (particularly in the wake of events at Fukushima in March 2011).[62–64] These policy decisions are broadly reflected in public opinion in each country, with the UK public more favourable to *fission* than the German public.[65] To the extent that nuclear *fusion* was seen as comparable to *fission*, either because of: (a) a wrongful conflation of the options; or (b) the correct classification of them as distinct but similar, centralized power generating options, could help to explain the discrepancies in opinion. Specifically, where *fission* and *fusion* were wrongly seen to be the same technology, to the extent that *fission* is a preferred option in the UK context, one might expect more preferable opinions among the UK respondents. Similarly, where the technologies were viewed as distinct, one might anticipate greater favourability within the UK due to recent high-profile endorsement of, and investment in, large centralised generating options (e.g. the Hinkley Point 'C' nuclear *fission* plant).[66] Indeed, particularly among German respondents familiar with the 'Energiewende'– which evidenced a strong preference away from centralised power generation – the prospect of hosting future, large-scale nuclear *fusion* facilities could have been seen as incongruous and, hence, a less attractive prospect.[67,68]

4.1 Limitations

There are certain limitations to the current research design, which mean that one should exercise caution when seeking to generalise from the study findings. For instance, the respondents, although purposively sampled to be demographically diverse (in terms of age and gender), were, for pragmatic reasons: (a) recruited solely through an online survey-panel provider (thus excluding those not registered to this panel-provider); and (b) were not purposively recruited on the basis of other socio-demographic characteristics that could influence perceptions of technological innovation (e.g. religiosity, political beliefs).[6,69,70] Where possible, we argue that future research could usefully explore the findings from the current study in more broadly representative national samples; and perhaps look to draw comparisons with populations from other countries. For instance, the prominence of centralised nuclear *fission* generation in France might be expected to render public opinion toward nuclear *fusion* more favourable than in Germany.

Aside from matters of participant recruitment, the limitations principally relate to how information was presented to participants within the study. For example, there is a question as to whether or not the nature and extent of the stigmatizing impact of DU observed in this study would have been different in the absence of initial efforts to inform people about nuclear *fusion* (helping to delineate it from nuclear *fission*). There are also questions as to whether or not the inherent credibility and trustworthiness of the CCFE, who were identified to participants as being associated with the project, might have rendered the information more persuasive than if their involvement in the project remained unstated. Indeed, while the information provided was designed to be accessible, informative and unbiased, to the extent that the CCFE were recognised as experts and proponents of nuclear *fusion*, their affiliation to the project might have inflated the tendency for participants to respond favourably to the information provided.[58,71] Furthermore, identifying the CCFE (and the University of Surrey) as the organisation(s) responsible for the study – being UK-based organisations – might also help to further explain the relative preference for nuclear *fusion* among the UK respondents. In light of this limitation, we recommend that future research could seek to vary, restrict or delay details of the source of the information in order to test the impact that source trust and credibility might have on stated preferences for nuclear fusion following the receipt of information.

Relatedly, and although quite subtle, the information provided to participants in this study inferred that all nuclear *fission* plant utilise *enriched uranium* as a fuel source. While this is the case for the most prevalent nuclear *fission* plant (hence our decision to present the information in this way), other reactor types utilise other fuel sources (e.g. unenriched uranium).[34] To the extent that participants differentiated between different forms of uranium within our study (e.g. *enriched uranium* was less favourable than uranium), one might hypothesise that a refocusing or broadening of the information provided to participants in order to recognise this diversity *could* yield slightly different results; particularly where preferences for nuclear *fusion* were anchored to beliefs about *fission*. Future research could thus usefully investigate whether the same trends in responses persist in situations where more comprehensive information about nuclear *fission* is provided to respondents.

Finally, in an experimental sense, it may have been preferable to investigate the stigmatizing impact of DU in isolation of references to the term *nuclear*. This would have provided a clearer indication of the unique stigmatizing effect that the term DU on attitudes towards *fusion.* That said, we sense that public discussions pertaining to the use of DU in the context of nuclear *fusion*, will likely only occur in the presence of the nuclear term at present. As such, we feel that our decision to investigate the branding effect yielded by the term DU alongside the term nuclear provides the research with a greater degree of ecological validity.

5 Conclusion

The findings of this study illustrate that the proposed use of DU for storing tritium *does* exert a stigmatizing impact on attitudes towards nuclear *fusion*. However, they also illustrate that there are reparative consequences of provisioning clarifying information about the nature and purpose of DU in relation to its proposed use in nuclear *fusion*. More specifically, our findings would suggest that attempts to: (a) emphasise the *positive use-value* of the material; and (b) to delineate DU from more radioactive forms of uranium, should serve to limit the potential for stigmatization occurring from this association.

In general, and consistent with the findings of similar research focused on public perceptions of other industrial-scale innovation (e.g. large-scale renewable energy and energy storage technologies; carbon capture utilisation and storage technologies)[5,47,72,73] we argue that that the results of this study point to the value of engaging publics in discussion about the relative acceptability of *fusion* as a possible, future power-generating option. Such engagement will be important in helping to delineate nuclear *fusion* as a technology and to correct any extant misperceptions so as to promote a more informed debate. We feel that such activity will be increasingly important as proposed commercial-scale demonstrations of the technology, like ITER, enter the public consciousness.

Relatedly, we sense that the low levels of self-claimed knowledge and awareness of nuclear *fusion*, in addition to the marked changes in attitudes proffered by the provision of small amounts of information about *fusion* vs. *fission* (Time 1 – Time 2) and the nature and purpose of DU (Time 3 – Time 4), are indicative of the relative malleability of public opinion towards nuclear *fusion* at this time. While this malleability clearly presents opportunities for those wishing to foster public support for the technology, there are also affiliated risks. For instance, one might anticipate that failures in public communication and engagement strategies (or a failure to engage *per se*) or labelling could result in attitudes moving from a position of tentative acceptance (or ambivalence) to one of opposition.

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Competing Interests

The authors know of no financial or non-financial competing interests relating to this study.

Materials and Correspondence

All correspondence and materials requests should be directed to the lead author.

Table 1. Key socio-demographic characteristics of UK and German sub-samples

		UK		Germany		Sig.
		N = 438		*N* = 390		
		Freq.	%	Freq.	%	*p*
Gender	Male	214	48.9	202	51.8	= .435
	Female	223	50.9	187	47.9	
	Other	1	0.2	1	0.3	
Age (years)	18-24	58	13.2	54	13.8	= .004
	25-34	75	17.1	81	20.8	
	35-44	69	15.8	79	20.3	
	45-54	80	18.3	86	22.1	
	55-64	97	22.1	60	15.4	
	65-74	50	11.4	29	7.4	
	75-84	9	2.1	1	0.3	
Nationality	Home country	396	90.4	357	91.5	= .048
	Other European	18	4.1	7	1.8	
	Other International	11	2.5	4	1.0	
	Non-response	13	3.0	22	5.6	
Employment Status	Employed (full/part)[1]	248	58.2	251	64.6	< .001
	Seeking employment	21	4.8	19	4.9	
	Homemaker	39	8.9	24	6.2	
	Student	19	4.3	36	9.2	

	Retired	82	18.7	42	10.8	
	Other	29	6.7	17	4.5	
Education	Secondary/High school	199	45.4	211	54.1	< .001
	University (undergrad.)	149	34.0	89	22.9	
	University (postgrad.)	55	12.6	56	14.4	
	No formal/Primary school	8	1.8	24	6.2	
	Other	27	6.2	10	2.6	
		Mean	SD	Mean	SD	*p*
Trust in science and scientists		3.31	0.61	3.30	0.58	= .381
Energy security concern		3.12	0.59	2.82	0.66	< .001
Biospheric values		4.07	0.83	4.12	0.86	= .917
Climate change concern	Personal	3.68*	1.25	3.52*	1.33	= .089
	Societal	3.91	1.21	3.86	1.23	= .562

Notes. [1]Includes full and part time paid employment, self-employment and military

Employment Other = unable to work, volunteer work and ‘other’

Education Other = technical college qualifications (e.g. HND, BTEC, City and Guilds); apprenticeship qualifications, emergency services qualifications (e.g. GIFireE) and International educational qualifications (e.g. International Baccalaureate).

*n = 436, n = 385

Table 2. Self-claimed awareness and knowledge of nuclear fusion and depleted uranium (DU)

		UK		Germany		
		Freq.	%	Freq.	%	Sig. (Fisher's exact test)
Awareness of nuclear fusion	Yes	219	50.0	248	63.6	$p < .001$
	No	219	50.0	142	36.4	
Confuse fusion and fission[1]	Yes	115	33.2	91	26.1	$p = .046$
	No	231	66.8	257	73.9	
Awareness of DU	Yes	232	53.0	197	50.5	$p = .487$
	No	206	47.0	193	49.5	
		Mean	SD	Mean	SD	Sig. (*t*-test)
Self-claimed knowledge of nuclear fusion		2.16	0.98	2.43	0.88	$t\ (826) = 4.15, p < .001, d = .29$
First heard about nuclear fusions		3.22	1.55	3.07	1.21	$t\ (813) = 1.56, p = .119, d = .11$
Self-claimed knowledge of DU		2.12	0.97	2.13	0.96	$t\ (826) = 0.12, p = .915, d = .01$

Notes. [1] Figures exclude those answering 'don't know' and non-respondents (n = 92 UK; n = 42 Germany)

Table 3. Mean evaluations of the different uranium terminology among the UK and German respondents

	UK		Germany		Overall		Country Comparisons
	Mean	SD	Mean	SD	Mean	SD	Sig. (*t*-test)
Uranium	3.95	2.18	3.62	2.23	3.79	2.21	*t* (826) = 2.11, *p* = .035, *d* = .15
Depleted Uranium	3.79	2.19	3.80	2.18	3.80	2.18	*t* (826) = 0.05, *p* = .959, *d* < .01
Natural Uranium	4.61	2.27	4.42	2.41	4.52	2.34	*t* (826) = 1.17, *p* = .244, *d* = .09
Enriched Uranium	3.81	2.28	3.05	2.22	3.45	2.28	*t* (826) = 4.80, *p* < .001, *d* = .33

Notes. Scale: 1 = Extremely uneasy; 10 = Extremely calm (hypothetical scale midpoint = 5.50); SD = Standard Deviation. Objectively, *depleted uranium* is less radioactive than the other forms of uranium outlined in this table. The *standard error* for all country comparisons is .08.

Table 4. Results of linear regression analysis predicting *Time 3* attitudes to nuclear fusion from attitudes towards depleted uranium

	UK				Germany			
	B	SE	ß	*t*	B	SE	ß	*t*
Negative Labelling[a]	.08	.03	.13*	2.48	.13	.03	.24***	4.71
Positive Labelling[b]	.02	.03	.03	0.65	-.01	.03	-.02	-0.35
Positive Use-Value[c]	-.42	.05	-.47***	-9.38	-.34	.04	-.42***	-7.78
Negative Use-Value[d]	.14	.06	.15*	2.25	.09	.06	.10	1.61
Negative Associations[e]	.02	.06	.02	0.29	.05	.05	.07	1.04
F		28.17				35.90		
R^2*adj.*		.26				.33		

Notes. Scale coding = 1 Strongly agree; 2 Agree; 3 Somewhat agree; 4 Neither agree nor disagree; 5 Somewhat disagree; 6 Disagree; 7 Strongly disagree

[a] *Negative labelling:* “Sounds more hazardous than uranium”. [b] *Positive labelling:* “Sounds less hazardous than uranium”. [c] *Positive Use-Value:* “Is not a particularly hazardous substance is used correctly”; “Has important industrial uses”; “Should be used in fuel storage for nuclear fusion technology (NFT)”; “Would improve my opinion of NFT if it were to be used in fuel storage”; “Is being put to good use by being used in NFT”. [d] *Negative Use-Value:* “Would negatively affect (tarnish) my opinion of NFT if used in fuel storage”; “Unduly increases the risks associated with NFT”; “Creates unwelcome links between fission and fusion industries”; “Would negatively affect public opinion of NFT in fuel storage”; “Would limit the countries in which nuclear fusion power stations could be built”. [e] *Negative associations:* “Has

negative affiliations with nuclear weapons"; "Is an inherently risky substance"; "Has negative affiliations with military ammunition"; "Has negative associations with terrorism".

** p < .05;** p < .01; ***p < .001*

Table 5. Mean evaluations of the sub-facets of attitudes towards depleted uranium at *Time 3* (pre-information about DU) and *Time 4* (post-information about DU)

	Time 3 Mean (SD)		*Time 4* Mean (SD)		Country and Temporal Comparisons
	UK	Germany	UK	Germany	Sig. (ANOVA)
Negative Labelling	3.76	3.96	4.32	4.32	Time: $F(1, 805) = 90.88, p < .001, \eta_p^2 = .101$
	(1.21)	(1.28)	(1.27)	(1.17)	Country: $F(1, 805) = 2.45, p = .118, \eta_p^2 = .003$
					Interaction: $F(1, 805) = 4.22, p = .040, \eta_p^2 = .005$
Positive Labelling	4.06	3.92	3.41	3.52	Time: $F(1, 781) = 70.64, p < .001, \eta_p^2 = .083$
	(1.47)	(1.60)	(1.50)	(1.59)	Country: $F(1, 781) = .013, p = .908, \eta_p^2 < .001$
					Interaction: $F(1, 781) = 4.10, p = .043, \eta_p^2 = .005$
Positive Use-Value	3.79	3.72	3.37	3.48	Time: $F(1, 787) = 88.36, p < .001, \eta_p^2 = .101$
	(1.06)	(1.12)	(1.14)	(1.16)	Country: $F(1, 787) = 0.02, p = .890, \eta_p^2 < .001$
					Interaction: $F(1, 787) = 6.22, p = .013, \eta_p^2 = .008$

Negative Use-Value	3.33	3.22	3.51	3.39	Time: F (1, 798) = 32.04, $p < .001$, $\eta_p^2 = .039$
	(1.01)	(1.01)	(1.02)	(1.10)	Country: F (1, 798) = 3.61, $p = .058$, $\eta_p^2 = .005$
					Interaction: F (1, 798) = 0.08, $p = .778$, $\eta_p^2 < .001$
Negative Associations	2.98	3.13	3.27	3.30	Time: F (1, 803) = 46.19, $p < .001$, $\eta_p^2 = .101$
	(1.08)	(1.16)	(1.10)	(1.25)	Country: F (1, 787) = 0.02, $p = .250$, $\eta_p^2 = .002$
					Interaction: F (1, 803) = 4.06, $p = .044$, $\eta_p^2 = .005$

Notes. Scale coding = 1 Strongly agree; 2 Agree; 3 Somewhat agree; 4 Neither agree nor disagree; 5 Somewhat disagree; 6 Disagree; 7 Strongly disagree

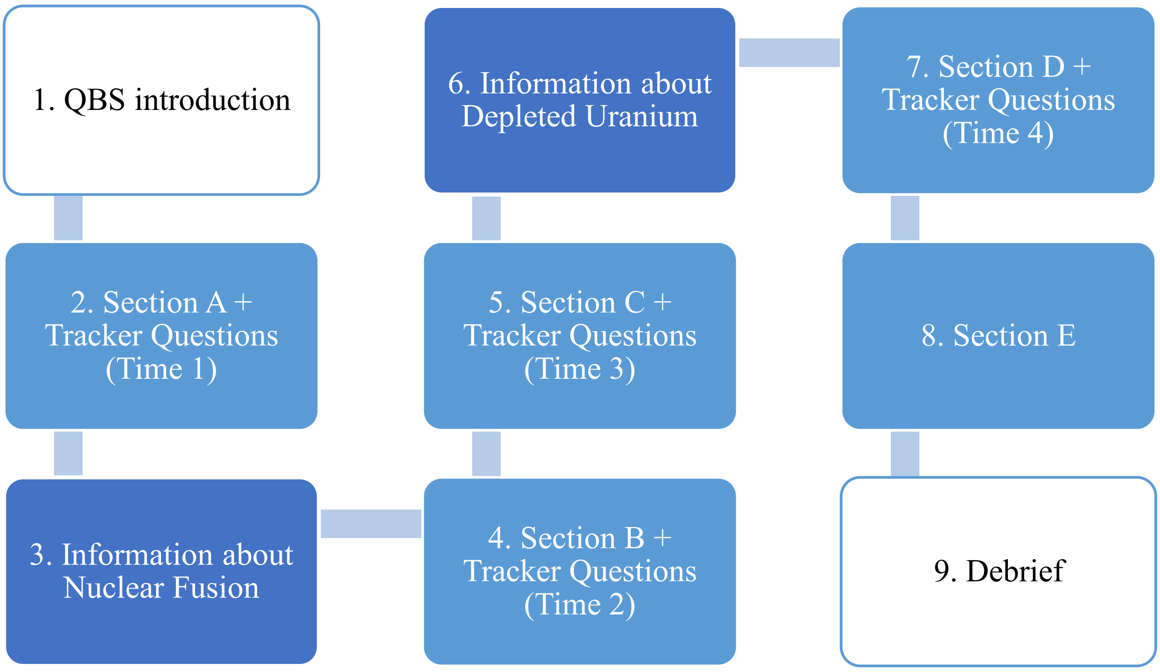


Figure 1. A diagram of the 9 stages comprising the flow of the questionnaire based survey (QBS).

Note. The survey comprised five question-based sections (Sections A-E), two sections where respondents were provided with information on nuclear *fusion* (3) and depleted uranium (6). These sections were 'book-ended' by a written introduction (1) and debrief (9).

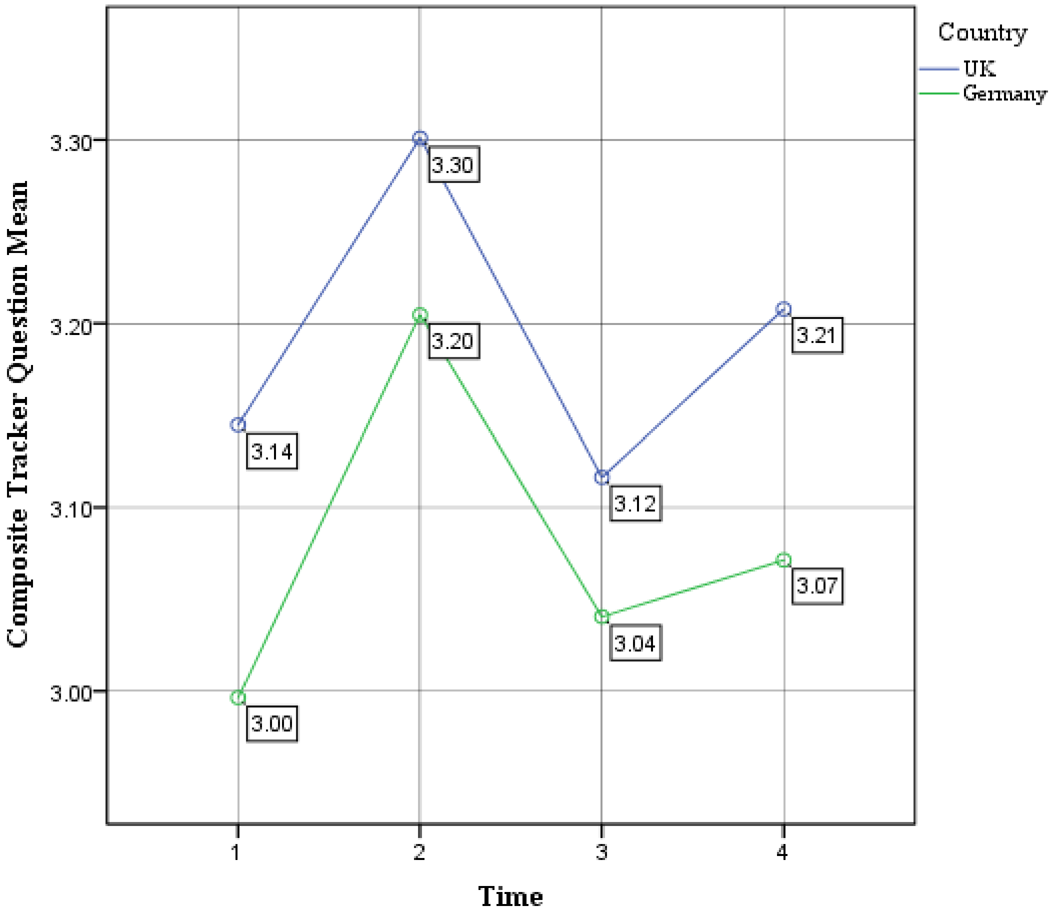


Figure 2. Composite tracker-question means for UK and German respondents at each of the four survey time-points.

Notes. 3.00 denotes the scale midpoint (higher values = more favourable towards nuclear *fusion*). Time 1 = pre-information about nuclear *fusion*; Time 2 = post information about nuclear *fusion*; Time 3 = pre-information about DU; Time 4 = post-information about DU.

Results of follow-up 2 (Time) x 2 (Country) repeated measure ANOVAs

Comparison	Time	Country	Interaction
(a) T1 – T2	$F = 71.00, p < .001, \eta_p^2 = .08$	$F = 4.70, p = .030, \eta_p^2 = .006$	$F = 1.15, p = .229, \eta_p^2 = .002$
(b) T2 – T3	$F = 109.70, p < .001, \eta_p^2 = .12$	$F = 2.09, p = .149, \eta_p^2 = .003$	$F = 0.36, p = .541, \eta_p^2 < .001$
(c) T3 – T4	$F = 15.41, p < .001, \eta_p^2 = .02$	$F = 2.91, p = .089, \eta_p^2 = .004$	$F = 3.79, p = .052, \eta_p^2 = .005$

Note: All analyses $df = 1, 826$

Appendix A

Table A1.

Key demographic, knowledge and awareness questions (and response coding) from Section A of the survey.

Demographics		
Age	What age bracket are you in?	18-24; 25-34; 35-44; 45-54; 55-64; 65-74; 75-84; 85+
Gender	What is your gender?	Male; Female; Other; Prefer not to say
Education	Please select the option that best represents your level of education	No formal schooling completed; Primary; Secondary/High; UGrad university degree (a) enrolled or (b) awarded; PGrad university degree (a) enrolled or (b) awarded; Other
Employment	What is your current employment status?	Employed (full or part time); Self-employed; Out of work/job seeking; Homemaker; Volunteer; Student; Military; Unable to work; Retired; Other
Nationality	What is your nationality?	Free response

Initial Awareness and Knowledge of Nuclear Fusion Technology (NFT)		
Fission/Fusion Confusion	Before today, did you think that fusion and fission were the same?	Yes; No; Don’t Know
Awareness	Before today, had you heard of NFT?	Yes; No

Self-claimed Knowledge	How much would you say you currently know about NFT?	Nothing (I have never heard of it); Nothing (I have only heard the name); A little; A fair amount; A lot
First heard of NFT	When was the first time you heard about NFT?	A long time ago; Not very recently; Fairly recently; Very recently; Today

Notes: Additional questions included in Section 1 that are not considered in this article assessed: (1) if currently employed, what is your occupation (free response)?; (2) If you had heard of NFT before today, where was this from? (12 source options, e.g. School; Television/Radio News; Social Media); and (2 What are the first three words or phrases you associate with NFT? (Free response)

Supplementary Material

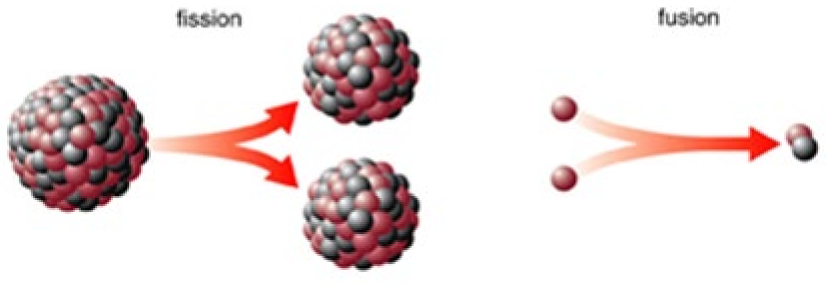
Section 3 (*"Information about Nuclear Fusion"*) and Section 6 (*"Information about Depleted Uranium"*) of the questionnaire-based survey (see Figure S1) comprised the following brief passages of information (including associated diagrams), prepared by nuclear fusion communication experts at the Culham Centre for Fusion Energy (CCFE).

Section 3: Nuclear Fusion Technology

Currently, nuclear power stations produce energy using a process called nuclear fission. This involves splitting large atoms into smaller atoms in order to release energy to power the electricity generating process (see the picture below).

A different process, called nuclear fusion, produces energy inside the core of the sun. This involves fusing smaller atoms into larger ones in order to release energy. Scientists around the world are attempting to replicate this process, developing nuclear fusion technology to be used to generate electricity in future power stations.

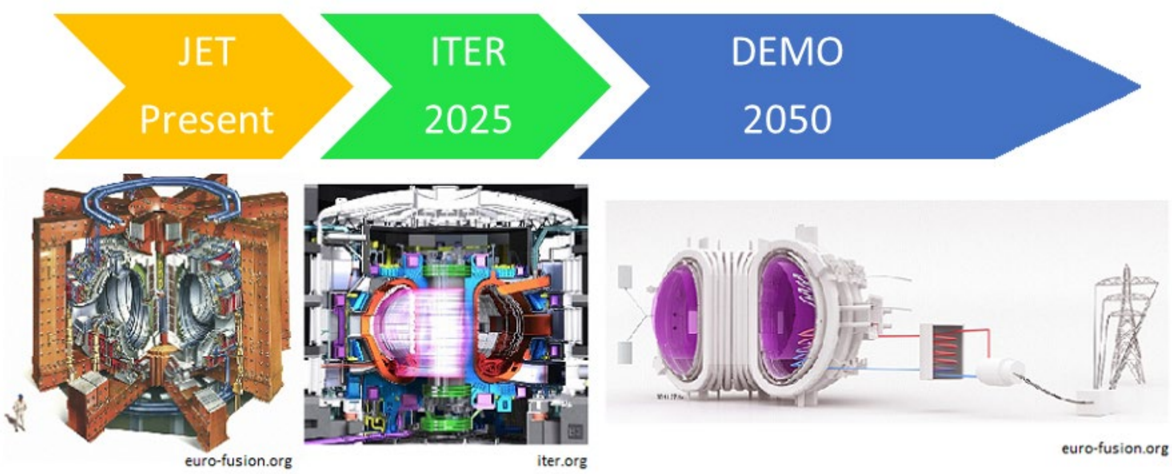
The fuel for nuclear fusion power generation is hydrogen – or more specifically, different types (or isotopes) of hydrogen called deuterium and tritium. In order for nuclear fusion reactions to occur, deuterium and tritium gas must be mixed and heated to temperatures of over 100 million °C within a nuclear fusion reactor.



Nuclear Fission vs. Nuclear Fusion
(Source: nuclear.duke-energy.com)

The Joint European Torus (JET) in Oxfordshire, UK, is currently the world's most powerful experimental nuclear fusion reactor. This experimental reactor has been operating for over 30 years and it is an important part of the wider European "roadmap to fusion electricity" (i.e. the journey that we must take in order to build a fully functioning nuclear fusion power station).

The next step on the "roadmap" is the construction of a larger and more powerful experimental nuclear fusion reactor called ITER. ITER is currently being constructed in a place called Cadarache in the south of France. ITER is planned to be up and running by 2025 and will be the first experimental nuclear fusion reactor capable of producing significantly more energy than it uses to create the nuclear fusion reaction.



euro-fusion.org iter.org euro-fusion.org

Timeline for nuclear fusion development

ITER will be a springboard to a full-scale demonstration nuclear fusion power station called DEMO. DEMO will be located somewhere in Europe (the site has not yet been specified) and is planned to be completed and operational around 2050. DEMO will be the first nuclear fusion reactor able to provide electricity to the European electricity grid for use in powering homes and businesses.

Below is a table outlining some of the proposed advantages and disadvantages of nuclear fusion technology (NFT). Please read the text in the table carefully and then answer the questions that follow.

ADVANTAGES of nuclear fusion	**DISADVANTAGES of nuclear fusion**

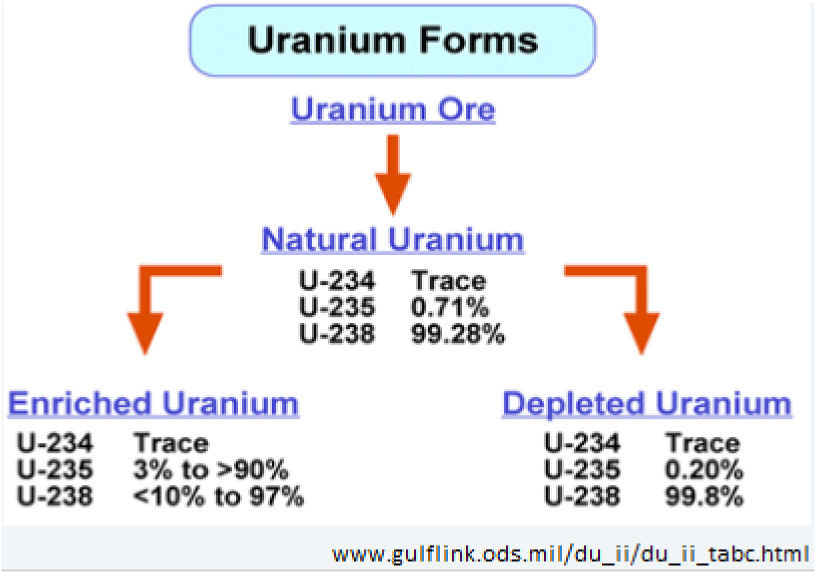
Sustainable and abundant energy Fusion fuels are widely available and are nearly inexhaustible. The nuclear fusion reaction releases 4 million times more energy than burning coal, oil or gas and four times as much as nuclear fission reactions.	**Impact on energy demand** As nuclear fusion power would produce large amounts of energy, it is possible that this would remove societal incentives for restraint or reduction of energy use.
No Carbon Dioxide (CO2) and no high-activity or long-lived radioactive waste Fusion power does not emit CO2 or other greenhouse gases into the atmosphere at the point of power generation. The only major by-product is helium, a non-toxic gas. The fusion reaction does not produce long-lived, high-radioactivity waste products.	**Radioactive fuel and low-level radioactive waste products** Tritium (hydrogen 3), a radioactive isotope of hydrogen, is used to power the nuclear fusion reaction. Tritium can be harmful if inhaled, ingested or touched. The nuclear fusion reaction also produces some short-lived radioactive waste products.
No risk of nuclear meltdown Fukushima-type nuclear accidents are not possible in fusion power stations. It is difficult to reach and maintain the precise conditions necessary for the fusion reaction to occur. If a disturbance occurs, the reaction stops within seconds. The quantity of fuel present in the reactor at any one time is only enough for a few seconds of fusion	**No full scale electricity production expected until 2050** Nuclear fusion technology is still being researched and developed. At present there are no operational commercial nuclear fusion power stations. It is anticipated that the first full-scale power station will not be operational until 2050. At present the research-scale demonstrations like JET use more energy than they produce.

as such there is no risk of a runaway nuclear chain reaction.	
Operating costs Similar to nuclear fission (which is used currently in nuclear power generation); when a nuclear fusion power station is up-and-running, the operational costs (e.g. fuel costs) will be cheap, meaning the electricity generated should be affordable.	**Start-up costs** There are high start-up costs associated with bringing nuclear fusion power 'to market'. While these start-up costs will likely reduce over time through research and development, some believe that the money invested in nuclear fusion would be better invested in other options, like renewables.
Adapted from www.ITER.org	

Section 6: Depleted Uranium

What is depleted uranium?

Uranium is a naturally occurring metal found in rocks and seawater. Uranium can be enriched using industrial processes to increase the amount of the isotope U-235 (see the picture below). Slightly enriched uranium is used as fuel in nuclear fission power stations and highly enriched uranium can be used in nuclear weapons. Depleted uranium is left over from the enrichment process. It contains less of the U-235 isotope than natural uranium, so it cannot be used as nuclear fuel. Depleted uranium is 40% less radioactive than natural uranium and it is not classified as a dangerous substance radiologically according to the World Nuclear Association.



www.gulflink.ods.mil/du_ii/du_ii_tabc.html

Why is depleted uranium used to store the fusion fuel?

Hydrogen is a flammable gas and the hydrogen isotope (i.e. tritium) used as fuel for nuclear fusion is also radioactive. This means that safety is the priority when considering storage options for this fuel. Storing the tritium as a solid chemical compound known as a "metal hydride" is safer than storing it as a gas. By passing the tritium gas over depleted uranium in a secure metal containment vessel (i.e. a depleted uranium "bed" - see the picture below) you create this solid metal hydride.

Due to its chemical properties, uranium is a very suitable metal for storing tritium as all the stored tritium can be easily recovered and reused after storage. Depleted uranium is currently used to store the tritium fuel for the JET fusion experiments taking place at the Culham Centre for Fusion Energy, as it is currently considered to be the safest and most suitable fuel storage method.

Depleted uranium is also the favoured option for use in ITER (i.e. the next nuclear fusion demonstration facility). Alternative storage materials, such as zirconium-cobalt and titanium, are being investigated for use as tritium storage options. Currently these alternatives are not favoured as much as depleted uranium as they are less efficient (e.g. they do not allow you to recover and reuse all of the stored fuel).

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Outlined below are some of the proposed advantages and disadvantages of using depleted uranium as a tritium storage option. Please read the text carefully and then answer the questions that follow.

Advantages of depleted uranium:

- Using depleted uranium is considered to be a safe and reliable means of storing tritium, as tritium can be easily captured and stored at room temperature.
- All stored tritium can be accessed when required. This is due to the fully reversible chemical reaction between uranium and hydrogen. This is not the case with other metals that can be used to store tritium, such as zirconium-cobalt or titanium, in which some of the tritium remains trapped.
- A waste route for disposing of the depleted uranium 'beds' used to trap the tritium already exists. The resulting waste is classed as low-level waste.

Disadvantages of depleted uranium:

- There are some occupational hazards that need to be considered and controlled for when using depleted uranium.
- Depleted uranium is chemically toxic if touched, inhaled or ingested.
- Depleted uranium is pyrophoric (can ignite spontaneously in air) when in powder form.
- Depleted uranium is a radioactive substance. Despite not being used in nuclear weapons or in nuclear fission power generation, depleted uranium is classed as a nuclear material.

Consequently, there are strict regulations and controls applied to the use of depleted uranium. This could be an issue that influences the choice of country for the location of DEMO, the full demonstration fusion power station, intended to be operational in 2050.