The 2022 UK PONI Annual Conference

A Collection of Papers from Emerging Nuclear Experts

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UK PROJECT ON NUCLEAR ISSUES

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The UK Project on Nuclear Issues (UK PONI) is a cross-generational network of over 1,700 registered members which encourages young scholars and professionals to engage with established experts on contemporary nuclear issues.

The project aims to support the development of a tightly knit community of emerging voices that have the potential to influence the nuclear field.

UK PONI's mission focuses on the following three core aspects.

Connecting Across Boundaries

UK PONI draws together the broad range of communities of emerging nuclear specialists, principally addressing the technical–policy, senior–junior, government–non-government, and military–civilian divides. UK PONI will continue to engage with the civil nuclear community and to provide specialists in nuclear weapons issues with some exposure to civil nuclear issues, but it will do this in partnership with similar organisations in the civil nuclear sector, rather than seeking to develop a distinct new offering.

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UK PONI provides knowledge and skills development opportunities for its members that can be directly tied to their personal development plans. This incorporates continued efforts to promote diversity of inclusion and representation in the opportunities and platforms provided by UK PONI events and activities, and the formalisation, with a range of suitable partners, of its commitment to diversity and inclusion.

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More information about the project and its core programme of activities can be found on the new website, ukponi.rusi.org/

UK PROJECT ON NUCLEAR ISSUES

Editors' Note

Ana Alecsandru and Jack Crawford

For the first time since 2019, nuclear experts and practitioners gathered in person in June 2022 for the UK PONI Annual Conference in London. This hallmark UK PONI event provided attendees with a platform to engage in a diverse, informed dialogue on pressing nuclear topics. This edited collection represents a selection of the papers presented at the conference.

The nuclear field had an eventful 2022. Russia's threats of nuclear weapons use in its ongoing invasion of Ukraine have served as staunch reminders of the risks of nuclear weapons and their role in armed conflict. The Russian attacks on Ukrainian nuclear power plants have also sparked discussions concerning the physical integrity of nuclear facilities – reactors, fuel ponds and radioactive waste stores – in armed conflicts.

The First Meeting of States Parties to the Treaty on the Prohibition of Nuclear Weapons (TPNW), organised in Vienna in June 2022, ended with the adoption of the Vienna Declaration, as well as a Plan of Action that provides a roadmap to implement the TPNW in all its aspects, including the positive obligation to redress the harm caused by nuclear weapons use and testing. In August 2022, the Tenth Review Conference (RevCon) of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) failed to result in an agreement, with Russia refusing to accept the final draft outcome document of a four-week review of the NPT Treaty.

The Joint Comprehensive Plan of Action in Iran faces an uncertain future, with prospects for returning to a nuclear agreement dimming. Additionally, China's relentless modernisation of its nuclear weapons capabilities continues, signalling – in conjunction with the issues listed above – an uncertain and possibly unstable next chapter of nuclear affairs.

However, the future of nuclear politics and policymaking is not necessarily bleak. During the PONI Annual Conference, speakers, panellists and attendees addressed potential concerns arising from these developments and offered fresh perspectives on how best to tackle and overcome potential challenges facing the nuclear field. The papers in this volume comprise research from panellists at the conference, representing their critical engagement with topics including: nuclear non-proliferation and disarmament; the UK nuclear enterprise; the sustainability of nuclear skills; future nuclear technologies; and the implications of China's nuclear modernisation.

The eight papers specifically engage with topics at the intersection of geopolitics and risk reduction, existing and future technologies, and sustainability.

Zuzanna Gwadera discusses a potential avenue for bilateral arms control discussions between China and the US. Lucy Millington summarises the existing effectiveness of breakout times in reducing nuclear risks, before suggesting how the accuracy of those breakout times could be improved.

Regarding China specifically, Jamie Withorne uses China's development of nuclear capabilities to assess the relationship between open source intelligence, campaign analysis and national nuclear strategies. Sara Bundtzen addresses how Russian and Chinese officials use carefully tailored narratives to shape how the international community discusses non-proliferation and arms control.

Josh Mulholland and colleagues assess how nuclear weapons in space could pose as tools for planetary defence, interplanetary travel, and extra-terrestrial terraforming. Robbie Lyons argues for the utility of small modular reactors in the UK's pursuit of more affordable nuclear power generation, while Alex Langton, Kate Taylor and Dan Whittaker and Lacey-Jo Marsland and Ben Goold offer pathways to a greener future for the UK in its pursuit of net zero through the use of nuclear energy.

Collectively, the 2022 edition of the UK PONI Papers features a snapshot of ideas and proposals from the newest generation of nuclear professionals and experts that signal their preparedness to tackle the challenges of today and tomorrow with unconventional ideas and new perspectives.

UK PONI is funded and supported by a consortium of government and industry stakeholders. This support allows UK PONI to maintain an independent forum where emerging scholars can contribute new ideas on ongoing nuclear issues. In addition, UK PONI enjoys the support and guidance of its Board of Advisors, which includes representatives from government, industry, the military and academia.

UK PONI would like to express gratitude to its partners and sponsors for their continued support, especially the Atomic Weapons Establishment, Lockheed Martin UK, the UK National Nuclear Laboratory, Babcock, BAE Systems, MASS, the UK Ministry of Defence, and Rolls-Royce.

These papers were accepted in September 2022 and the information therein was current at the time of writing. All views expressed are the authors' own and do not necessarily reflect those of the authors' institutions, UK PONI nor RUSI.

I. Assessing State-Sponsored Online Information Operations Related to Nuclear Non-Proliferation and Arms Control

Sara Bundtzen

Since Russia's invasion of Georgia in 2008, and even more so since its annexation of Crimea in 2014, Western foreign policy circles have regularly stressed the evolving role of 'hybrid threats' in the international security landscape. According to NATO, the methods of hybrid warfare 'are used to blur the lines between war and peace, and attempt to sow doubt in the minds of target populations'.[1] Throughout Russia's ongoing military invasion of Ukraine, analysts have shown how conventional warfighting is being accompanied by state-sponsored propaganda and narratives that peddle false and manipulated information, targeting global audiences.[2]

In March 2022, NATO Allies exposed 'Russia's fabricated narratives or manufactured "false flag" operations' that sought to justify its invasion.[3] Allies also called on the People's Republic of China (PRC) to 'cease amplifying the Kremlin's false narratives'.[4] Among its many narratives, the Kremlin promoted a false threat picture stemming from alleged WMD in Ukraine.[5] PRC diplomats and Chinese state-controlled media echoed Russia's allegations of chemical and biological weapons laboratories, while replicating Russian rhetoric of a 'special military operation' in Ukraine.[6] Russian and PRC accounts use the widespread accessibility and reach of mostly US-based social media platforms to promote their narratives among foreign audiences.

This paper looks at Russian and PRC activities on social media, focusing on nuclear non-proliferation and arms control issues. Specifically, it addresses the question: what narratives and tactics do Russian and PRC official accounts use to influence the international discourse related to nuclear non-proliferation and arms control?[7]

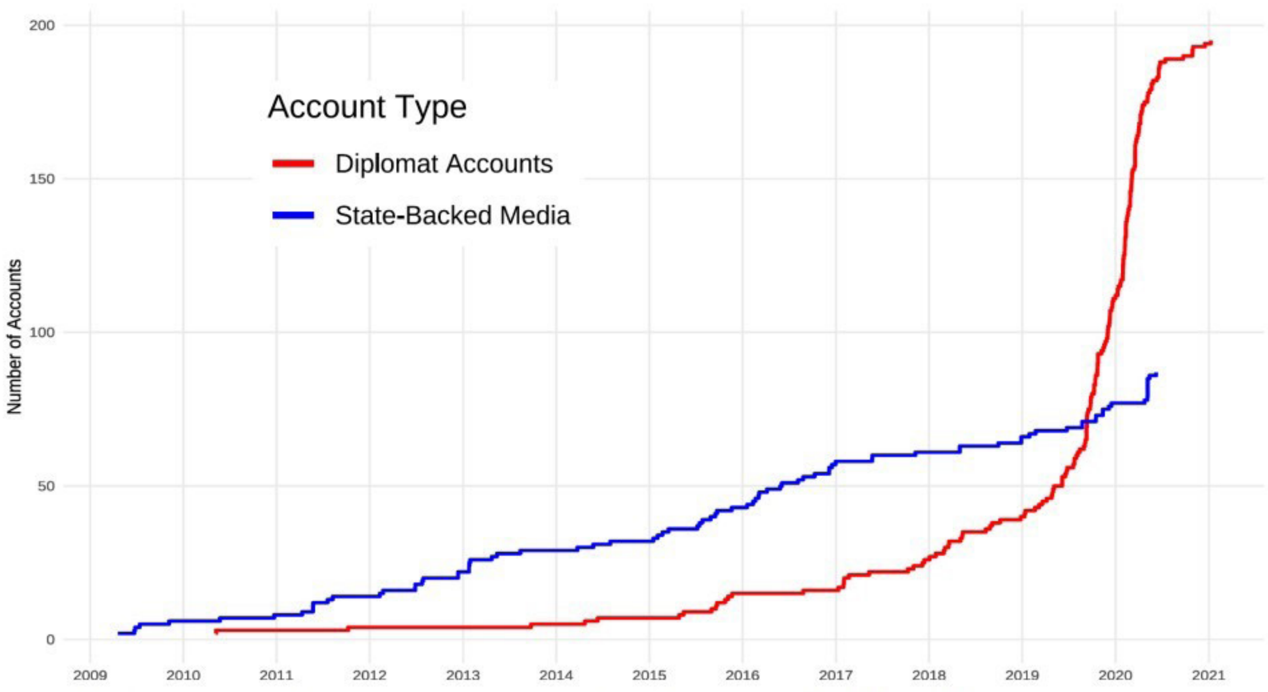
The paper focuses on Russia and China as significant players in the global nuclear architecture, representing two of the five nuclear weapon states in the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Policymakers and diplomats working on nuclear non-proliferation and arms control should thereby develop an understanding of Russian and PRC use of the online space for information operations. The paper concludes with recommendations to NATO Allies, specifically addressed to those working in strategic communication and intelligence production.

Research Methodology and Scope

In recent years, developing methodological approaches to studying social media manipulation has become an important means for monitoring and analysing information operations. While there are major hurdles to studying platforms because of limited data access, some technology companies, such as Twitter, have offered application programme interface (API) access that permits the analysis of content posted on their services. Following Elon Musk's Twitter takeover, it is yet unclear whether and to what extent API access to the platform for external researchers may be restricted in the future.

This paper conducts a qualitative narrative analysis focusing on English-language content posted by Russian and PRC official accounts on Twitter. The selected scope takes into account evidence signifying the relevance of the platform for Russian and PRC public diplomacy efforts.[8]

Figure 1: Number of PRC Diplomat and State-Backed Media Accounts on Twitter



Source: Marcel Schliebs et al., 'China's Public Diplomacy Operations: Understanding Engagement and Inauthentic Amplification of PRC Diplomats on Facebook and Twitter', Programme on Democracy and Technology, Oxford Internet Institute, University of Oxford, 11 May 2021, <https://demtech.oii.ox.ac.uk/wp-content/uploads/sites/127/2021/05/Chinas-Public-Diplomacy-Operations-Dem.Tech-Working-Paper-2021.1-4.pdf>, accessed 10 October 2022.

Note: Diplomats include embassies, ambassadors, consuls and consulates. State-backed media outlets include 10 of the largest state-controlled media entities. Y-axis measures cumulative number of active accounts.

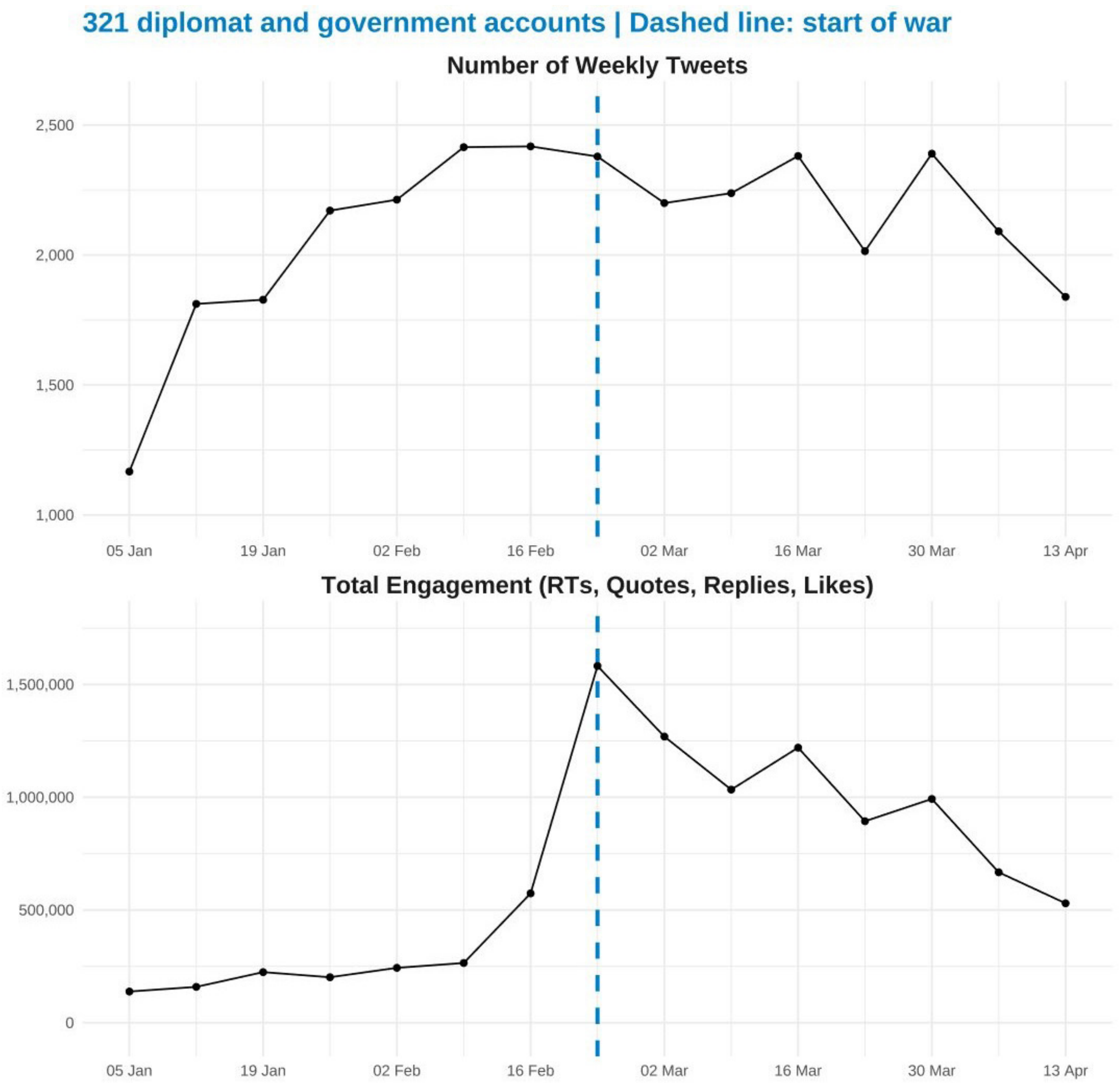
For example, the Oxford Internet Institute (OII) analysed the activities of 189 Twitter accounts belonging to PRC diplomats between June 2020 and February 2021.[9] Researchers found that account numbers rapidly increased (see Figure 1) and were highly active, tweeting an average of 778 times a day for a nine-month period. The accounts were posting content in line with PRC messaging targeted at an international audience.

Another study, by the Australian Strategic Policy Institute, focused on PRC messaging on Ukraine. The study found that PRC diplomats on Twitter used 21 different languages and tailored framing to different regions, while nearly 75% of the content was in English.[10] The observed narratives were directly linked to China's political security strategy, designed to shape its operating environment so that the party-state's power can be consolidated and expanded, domestically as well as globally.

Similarly, Russian actors began conducting information operations on Twitter began as early as 2014, particularly via the Internet Research Agency (IRA), to interfere with the US political system.[11] In 2018, Twitter found more than 3,000 accounts affiliated with the IRA, including more than 10 million Tweets.[12]

More recently, the OII tracked 321 official Russian accounts on Twitter between January and April 2022, finding that they posted over 2,000 times a week and gained over 1 million engagements (see Figure 2).[13]

Figure 2: Weekly Twitter Activity and Engagement with Russian Accounts



Source: Marcel Schliebs, Twitter post, 26 April 2022, <https://twitter.com/m_schliebs/status/1519015144466042880>, accessed 10 October 2022.

This paper used lists of official Russian and PRC accounts[14] and queried for thematic keywords related to nuclear non-proliferation and arms control, such as 'INF treaty' or 'JCPOA', using Twitter's Brandwatch monitoring tool.[15] The narrative analysis reviewed the data qualitatively to allow for thematic nuances.

Information Operations, Information Disorder and Narratives

This paper considers state-sponsored information operations as a continuous adaptation of Soviet-era 'active measures', which sought 'to deceive the target (foreign governmental and non-governmental elite or mass audiences) and/or to distort the target's perception of reality'.[16] Information operations evolved alongside the digitally connected global information ecosystem. In particular, social media has become a new operational arena in which information flows and channels are characterised by greater speed, diffusion and reach. This enables state actors to target and reach different audiences globally, without requiring sophisticated technology, at low risk and low cost.

In order to explain the online information environment, Claire Wardle identified multiple forms of information disorder: satire or parody can be used to intentionally spread rumours and conspiracies; misleading content can include fragments of quotes or selectively chosen statistics; imposter content impersonates genuine sources; false connections rely on sensational language and clickbait headlines, while false context reframes genuine information using false contextual information; manipulated content alters videos or photos; and fabricated content spreads false information. Information operations often use a combination of all forms and, as Wardle emphasises, 'anything with a kernel of truth is far more successful in terms of persuading and engaging people'.[17]

When studying the online information space, researchers frequently refer to 'narratives'. This term has no single universally accepted meaning, but has been defined as 'deriving moral judgements from stories'.[18] Essentially, narratives may or may not carry information disorder, but they typically reduce complexity and offer a 'vision' or 'perception' of some sort of (achievable or non-achievable) end-state, for example, constructing a shared meaning of international politics.[19] Relying on ambiguity and blurriness, narratives often benefit from simplified, decontextualised or manipulated content. They might be designed to reinforce policy, to explain a 'rationale' for conducting an activity and the outcome sought, or simply to distort the discourse. This paper identifies and analyses narratives contained in the Tweets of Russian and PRC official accounts, further outlining the tactics used to convey such narratives.

Key Findings of the Narrative Analysis

Russia: Instilling Doubt and Sowing Distrust

Deny and Deflect from Treaty Non-Compliance

Official Russian accounts frequently denied any evidence of Russia's non-compliance with the Intermediate-Range Nuclear Forces (INF) Treaty, including claims that there was 'no single shred of evidence' of such non-compliance (see Figure 3).[20] Posts diverted attention from Russia's responsibility using unrelated and misleading comparisons with the Iraq War, for example, referring to 'the shameful story about "WMD of Saddam Husein"' (see Figure 4). Posts also made false counter-accusations, claiming 'Washington's true goal' had been to 'get rid of restrictions' (see Figure 5). Overall, narratives place all blame for the demise of the INF Treaty on the US administration.

Figures 3, 4 and 5: Sample Posts from Official Russian Accounts on Twitter

Figures 6 and 7: Sample Posts from Official Russian Accounts on Twitter

Undermine Credibility of International Verification

Official Russian accounts insinuated that international verification of nuclear safeguards conducted by the International Atomic Energy Agency (IAEA) were subject to Western bias and politicisation (see Figures 6 and 7). One account claimed there is a trend of lacking 'factual accuracy' in multilateral diplomacy and politicising the work of the IAEA Board of Governors. Such claims deflect from Russia's military actions against Ukrainian nuclear facilities, which prevent IAEA inspectors from conducting safeguard verification activities.

Figures 8, 9 and 10: Sample Posts from Official Russian Accounts on Twitter

Inflate and Construct Evidence

Russian official accounts frequently accused Ukraine of attempts to develop nuclear weapons. Such allegations also claimed that NATO Allies would support Ukrainian nuclear proliferation (see Figures 8, 9 and 10). This narrative used selectively chosen statements, as in the case of Radek Sikorski, former foreign minister of Poland, who publicly suggested providing Ukraine with nuclear weapons. Sikorski argued that Russia broke the terms of the Budapest Memorandum on Security Assurance, meaning that nuclear weapons could be returned to Kyiv.[21] Russia's narrative of a nuclear threat in Ukraine used Sikorski's comments, claiming that the 'Western puppet masters' of Kyiv were urging that nuclear weapons be supplied to Ukraine. In another instance, official accounts promoted a manipulated video of the UK Defence Minister Ben Wallace speaking with Russian YouTubers who were pretending to be Ukraine's prime minister Denys Shmyhal. The video featured excerpts giving the impression that Wallace would support the development of a Ukrainian nuclear weapons programme. In another example, official accounts alleged Russia had 'clear evidence' that Ukraine 'was making [a] dirty nuclear bomb', creating a false threat picture and seeking to justify Russia's occupation of Ukrainian nuclear plants.

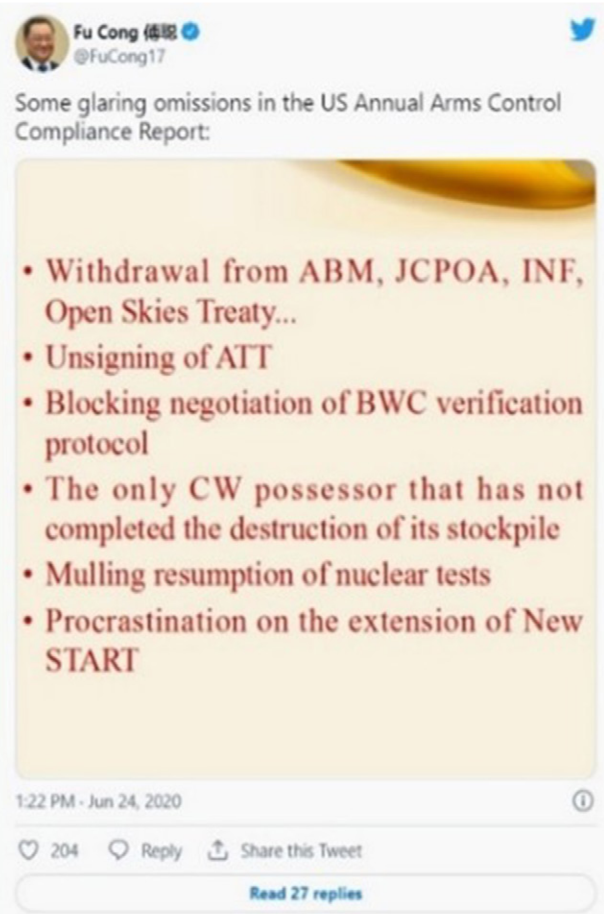
China: Shifting Global Attitudes in Favour of Political Security

Claim the Moral High Ground

In reaction to the Australia–UK–US (AUKUS) partnership, PRC accounts discredited Western 'moral authority' (see Figure 11) in the field of nuclear non-proliferation, accusing the West of 'double standards' (see Figure 12).[22] The posts claimed that AUKUS endangered international non-proliferation, further reinforcing China's longstanding criticism of Western security alliances such as NATO.[23] Moreover, posts frequently referred to the concerns of the international community, suggesting that China would act as a global leader addressing these concerns. Claiming the moral high ground in the field of nuclear non-proliferation fosters PRC messaging that portrays China as a responsible and normative leader in pursuit of a China-led global order.

Figures 11 and 12: Sample Posts from Official PRC Accounts on Twitter

Figures 13 and 14: Sample Posts from Official PRC Accounts on Twitter



Blame the US/West

PRC accounts often referred to 'wrongdoings' in the US approach to nuclear arms control and non-proliferation. Such posts mixed factual information with misleading critiques that simplified reality – for example, suggesting the US withdrew from the INF Treaty for no reason, despite Russia bearing considerable – if not sole – responsibility for the Treaty's demise.[24] PRC messaging also used the US decision to withdraw from the Iran nuclear deal to accuse the US of 'double standard', 'hegemonic thinking' and 'ugly hypocrisy' (see Figure 13).[25] In another instance, PRC accounts reacted to calls for Japan to contemplate hosting US nuclear weapons by emphasising China's security concerns about alleged 'NATO duplication' in Asia, which would 'plunge the world into fear and chaos'.[26] This narrative denounces US and NATO nuclear policy as being escalatory and accelerating nuclear proliferation.

Favoured Tactics: Whataboutism and Gaslighting

Narratives frequently use 'whataboutism', a rhetorical tactic that responds to an accusation of wrongdoing by claiming that an offence committed by the other side is similar or worse. The intention is to undermine the legitimacy of the original criticism.

Using whataboutism, Russian and PRC accounts routinely emphasised that the West's nuclear activities would be no different from their own, and that any condemnation by the West of its adversary's actions would therefore just reflect 'double standards' and 'hypocrisy'. Narratives often appeal to leftist discourses, using anti-hegemonic and anti-imperialistic rhetoric targeting the US. The underlying intention remains the same: to justify or praise one's own actions and deflect any blame to the other side.

Some narratives rely on 'gaslighting' tactics that spread false, decontextualised or manipulated content. Gaslighting intends to cause the other side to doubt their sanity through psychological manipulation. As such, Russia's narratives in the nuclear field intend to sow confusion and doubt about evidence or the verification process. These narratives do not necessarily aim to convince the audience of a particular truth, but rather to deny that there are any objective facts at all. In particular, confusion and the inability to find a factual common ground limit the prospects of negotiating future arms control agreements and risk paralysing legislative bodies such as Congress to ratify any such agreements.

Conclusions and Recommendations

The analysis in this paper outlines some of the state-sponsored narratives and tactics that NATO Allies and partners face in the field of nuclear non-proliferation and arms control. The findings are by no means complete given the limited scope of the paper. In addition, Russian and PRC accounts and narratives often react and adapt to international events.

Drawing from the findings, the following long-term recommendations are proposed:

1. Strategic communication teams and intelligence communities should advance situational awareness in the social media domain – including through monitoring and analysis capabilities – to better communicate and inform policymaking and diplomatic processes.

2. The efforts above should develop multi-platform and real-time monitoring capabilities to detect tactics as well as networks. For example, the analysis demonstrates a combination of official diplomatic communication alongside seemingly personal reflections from high-level officials. Such communication risks blurring the line between official positions and (semi-) covert information operations involving other proxy actors.

3. Strategic communications should not only reveal if information is misleading or false, but also develop clear policies that ensure coherent, transparent and factual information sharing early on. In most situations, when a narrative is 'out in the wild' and already in a self-reinforcing feedback loop, debunking efforts should focus on factual messages and sources to avoid giving the existing narratives more oxygen.[27]

4. Intelligence and research communities should invest in transparent, credible and professionalised open source intelligence capabilities. While a lot of crowd-sourced information gathering occurs, such investigations often have limited knowledge of the nuclear context, or can be misused for deceptive purposes (for example, false 'fact checks' or 'debunking'). A collaborative approach, together with the commercial sector, could advance codes of conduct, peer review processes and standards of evidence.

5. A whole-of-government and whole-of-society approach should aim to minimise societal and political vulnerabilities as well as gaps in media and digital literacy. In addition, building up public knowledge about international nuclear non-proliferation and arms control issues can pre-empt emerging information crises and uncertainties.

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7. 'Discourse' refers to 'accepted positions that constrain debates and shape worldviews; they are created and maintained through communication'. See Neville Bolt and Leonie Haiden, *Improving NATO Strategic Communication Terminology* (Riga: NATO StratCom Centre of Excellence, 2019), p. 29.

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14. Accounts include foreign affairs ministries, defence ministries, embassies, ambassadors, consuls and diplomatic staff (with or without Twitter's state-affiliated labels). The account collection relied on existing lists, including the web-based Hamilton 2.0 dashboard, as well as manual scoping of accounts.

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21. Russia’s claims frequently refer to a speech by Ukrainian President Volodymyr Zelensky at the Munich Security Conference in February 2022 in which he mentions the 1994 Budapest Memorandum, which ensures the territorial sovereignty of Ukraine in exchange for handing over its nuclear weapons inherited from the Soviet Union. In view of Russia’s violation of Ukrainian sovereignty, Zelensky demanded ‘a shift from a policy of appeasement to ensuring security and peace guarantees’. Ukraine is prohibited from acquiring nuclear weapons as it signed the NPT, and there is no evidence that the Ukrainian government is seeking to acquire nuclear weapons. See Roman Goncharenko, Tatjana Schweizer and Joscha Weber, ‘Fact Check: Vladimir Putin’s Victory Day speech’, *DW*, <https://www.dw.com/en/fact-check-vladimir-putins-victory-day-speech/a-61738068>, accessed 10 October 2022.

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II. A Window of Opportunity for Arms Control? Evolving Chinese Approaches to Crisis Stability

Zuzanna Gwadera

China repeatedly rejected the Trump administration's demands for it to join trilateral negotiations on arms reductions, citing the asymmetry in size of the US and Chinese nuclear arsenals.[1] While the numerical differences are undeniably true, China's ongoing nuclear modernisation has brought the country significantly closer to the US in terms of posture and force structure, with potential adverse effects on crisis stability. A hypothetical nuclear crisis between the two powers could be more rapid and unpredictable than ever before.

China has long expressed its scepticism about crisis instability and the value of nuclear escalation management. However, recent developments both in China's internal affairs and in regional geopolitics make engaging in forms of arms control that focus on crisis stability more appealing. This is because China is becoming increasingly aware of escalation risks, and because its own nuclear modernisation effort may be forcing Beijing to reconsider future military crisis scenarios.

This paper defines 'arms control' as 'all the forms of military cooperation between potential enemies in the interest of reducing the likelihood of war, its scope and violence if it occurs, and the political and economic costs of being prepared for it'.[2] This does not necessarily refer to the formal, treaty-based efforts targeting arms reductions. Rather, the measures should focus on reducing the risks of escalation and establishing crisis-management tools.

This paper argues that there is an opening for at least laying the groundwork for engaging China in bilateral arms control talks with the US to achieve risk reduction goals. It does not, however, aim to paint an overly optimistic picture. China is not ready for a detailed discussion of the size of its nuclear arsenal, its doctrine and potential crisis scenarios. There is deep mistrust between the US and China, and the political climate is unfavourable, as highlighted by the diplomatic crisis over former Speaker of the US House of Representatives Nancy Pelosi's visit to Taiwan in August 2022.[3]

While engaging China in meaningful crisis-oriented arms control will be difficult and time-consuming, the US must not postpone it to a more favourable political moment – that moment may never come.

Traditional Chinese Approaches to Nuclear Escalation and Arms Control

Crisis stability and nuclear escalation have not traditionally been a focus for Chinese research in the way they were for the US and the Soviet Union during the Cold War. Tong Zhao attributes this to the fact that China – not a direct participant in that conflict – has had relatively little experience with nuclear crises.[4]

The Chinese strategic community's discussion of the subject, which emerged in the late 1990s, indicates high levels of confidence in crisis stability – in other words, the belief that nuclear weapons are extremely unlikely to be used in a conflict.[5] For example, General Zhang Wannian, then chief of the General Staff Department of the People's Liberation Army (PLA), acknowledged in 1999 that 'modern limited warfare under high technology conditions is conducted under a cloud of a threat of becoming a nuclear war'.[6] He was, however, adamant that nuclear escalation was not an option, adding that 'this cloud or shadow of nuclear war will limit the scope of warfare'.[7]

Fiona Cunningham and Taylor Fravel argue that the main reason for this confidence is the Chinese experts' belief that, once nuclear weapons have been used in a conflict, further escalation cannot be controlled.[8] China's nuclear doctrine and force structure have generally been consistent with this notion: China has long pursued a strategy of assured nuclear retaliation and maintained a no-first-use (NFU) policy. In line with this, China's approaches to escalation management in conventional warfare are decidedly risk-prone. Military literature puts the emphasis on seizing the political and military initiative, even at great risk of further escalation.[9]

China's Increasing Awareness of Escalation Risks

As mentioned above, China itself has not been involved in many nuclear crises. In the past two decades, however, North Korea's growing nuclear capability and the resulting heightened tension with the US have brought scenarios of nuclear escalation to China's attention.[10] While China might not believe that nuclear weapons use is likely in a conflict in which it is actively involved, Beijing is keenly aware of the growing risk of a military conflict on the Korean Peninsula.

North Korea possesses an increasingly capable nuclear arsenal, but its early-warning capabilities are lagging behind.[11] During periods of military tensions, the necessity of operating in such a highly imperfect information environment will add to crisis instability. A further worry is North Korea's explicit quest to obtain tactical nuclear weapons, which would lower the threshold for use and make uncontrollable escalation more likely.[12]

A war featuring a potential nuclear exchange on the Korean Peninsula is an uncomfortable prospect for China, whose continued rise depends in part on regional stability. Additionally, the possibility of China becoming implicated in a potential US–North Korea nuclear crisis – for example, as the result of an accident – cannot be ruled out. China's unease over this risk was evident throughout 2017, when it increased its defences and military readiness along the Sino-North Korean border and discussed planning for potential conflict scenarios with the US.[13]

In parallel with these developments, the past decade of authoritative Chinese military writing has seen some progress in recognising the importance of the topic of crisis stability. The 2013 edition of *The Science of Military Strategy* states that 'as a crisis is inappropriately handled, it can create serious interference and destruction of … the nation's development and security, even affecting the historical process of China's rise', which could suggest an admission of the possibility of nuclear escalation.[14] Notably, the 2020 edition of PLA National Defense University's *Science of Military Strategy* distinguishes between deliberate and inadvertent military crises for the first time, having previously refused to acknowledge the difference.[15] Over the past few years, there has also been more literature emerging from Chinese civil society about the relationship between China's nuclear forces, posture and doctrine, and the impact on crisis stability.[16]

There have also been signs of interest in crisis stability and risk reduction in a more formal capacity. On 8 December 2021, the director-general of the Department of Arms Control of the Foreign Ministry, Fu Cong, expressed China's willingness to expand the scope of risk reduction dialogue at the P5 Process to include the impact on non-nuclear technologies such as AI and cyber capabilities on strategic stability, signalling that the Chinese government is increasingly thinking about the issue.[17] China has also been calling for all P5 states to affirm the Reagan–Gorbachev statement that 'a nuclear war cannot be won and must never be fought', and in January 2022, the five countries affirmed the statement in an unprecedented and welcome symbolic gesture, widely interpreted as a stepping stone to global risk reduction.[18]

Force and Posture Changes

Since China first acquired nuclear weapons, it has kept them on low alert, with reportedly no warheads operationally deployed. This reflects the conviction that China's nuclear weapons serve an exclusively defensive purpose and will only be used in retaliation after absorbing an enemy's first strike.

However, there are several political and technical indications that China may be moving towards a launch-on-warning posture. This posture, currently embraced by both the US and Russia, means that nuclear missiles are kept on high alert. It significantly reduces the time between the decision to use nuclear weapons and their launch, creating vulnerabilities to catastrophic misunderstandings.

Over the past decade, high-ranking officials have begun to call for China's nuclear forces to be put on higher alert, citing concerns over the credibility of their second-strike capability.[19] In 2020, a not long retired Chinese military official stated that China had shortened the reaction time to mere minutes to 'be able to carry out early warning nuclear counterattacks before enemy nuclear weapons land on the ground'.[20]

Additionally, as part of the modernisation process, China has been introducing weapons systems that are more conducive to launch-on-warning. A major development of the past decade was the introduction of a fleet of nuclear ballistic missile submarines (SSBNs). Having reportedly first deployed such vessels in the late 2000s, China has now launched six Type 094 submarines carrying intercontinental-range JL-2 ballistic missiles, thus achieving a fully operational sea-based deterrent.[21]

As Tong notes, China's deployment of SSBNs may have consequences for crisis stability. SSBNs are customarily fitted with ready-to-launch nuclear weapons, necessarily increasing their alert status. It may also be necessary to delegate launch authority to the submarine crew, which is a departure from the centralised command-and-control system and may heighten the risk of an unauthorised or accidental launch.[22]

Furthermore, in 2021, open source analysts found that Beijing was building more than 100 new silos for ICBMs in the northwest of the country.[23] Missiles in such fixed silos are more vulnerable and accurate, making them more suitable for a launch-on-warning posture. Notably, over the past two years there has been an uptick in Chinese technical literature on missile technologies that specifically mention 'launch-on-warning' applications.[24] China also seems to be working on strategic warning assets that would enable early incoming strike detection, and in 2019 President Vladimir Putin announced that Russia was assisting China in building a space-based early-warning system.[25]

Despite these developments, there has not yet been an official confirmation that China has increased the alert status of its forces. The recent technical advances, however, give Beijing more posture options and make it significantly easier to embrace launch-on-warning. If this were to materialise, it could indicate that China's conviction of the impossibility of nuclear weapons use is beginning to waver.

Importantly, adopting a launch-on-warning posture does not necessarily mean that China will abandon its long-standing NFU policy. But the shortened response time and greater reliance on early-warning systems means that future crises may become more unpredictable. The increased vulnerability to miscalculations and accidents might significantly accelerate escalation, making crises more difficult to control.

China is likely aware of this. The increasing symmetry between Chinese and US postures and force structure, while potentially destabilising, does provide the US with a strong argument when trying to engage China in crisis stability talks.

Recommendations

The US should clearly communicate, through both formal and informal channels, the intent of engaging China in crisis stability talks and the scope of potential measures. The US tends to portray risk reduction efforts as a contribution towards the fulfilment of their Nuclear Non-Proliferation Treaty Article VI commitments, but China does not want to pursue arms reductions and could easily interpret invitations to risk reduction dialogue as the first step towards disarmament.[26] The US could accompany such communications with unilateral measures to foster transparency and stability, such as clarifying that the US's anti-submarine warfare capabilities are not aimed at China.[27]

The US should pursue official bilateral engagement with China to develop a range of official dialogues, confidence-building measures and crisis management mechanisms, such as diplomatic channels or military protocols. Such talks would allow the states to focus on understanding each other's doctrines and threat perceptions. An example of a concrete goal of these talks could be for China to create a centre similar to the Nuclear Risk Reduction Centers that already exist in the US and Russia.[28] Further, developing new channels to assure Chinese leaders of US strategic intent in Korean Peninsula-specific crises could help reduce the chance of inadvertent conflict.

Following China's invitation, it is recommended that P5 countries should add discussion on non-nuclear technologies and crisis stability to the P5 Process dialogue. Clearly, in light of Russia's invasion of Ukraine, any P5 Process engagement in the near future remains extremely unlikely, but a continued dialogue on risk reduction is now more important than ever, and P5 countries should aim to continue the process. This could, for example, take the form of limited dialogues on the impact of a particular technology on crisis stability.

The international community should strive to keep the momentum going for engagement between Chinese and Western experts. This especially includes the resumption of the Track 1.5 nuclear dialogue between the US and China that was suspended in 2019.[29] Government organisations, international organisations and foundations should also commission in-depth studies that actively involve Chinese experts on subjects such as mutual threat perceptions and the escalatory potential of new technologies. Such studies could help identify areas with the most potential for risk reduction.

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III. Nuclear Waste: A Fuel or a Burden for the Future?

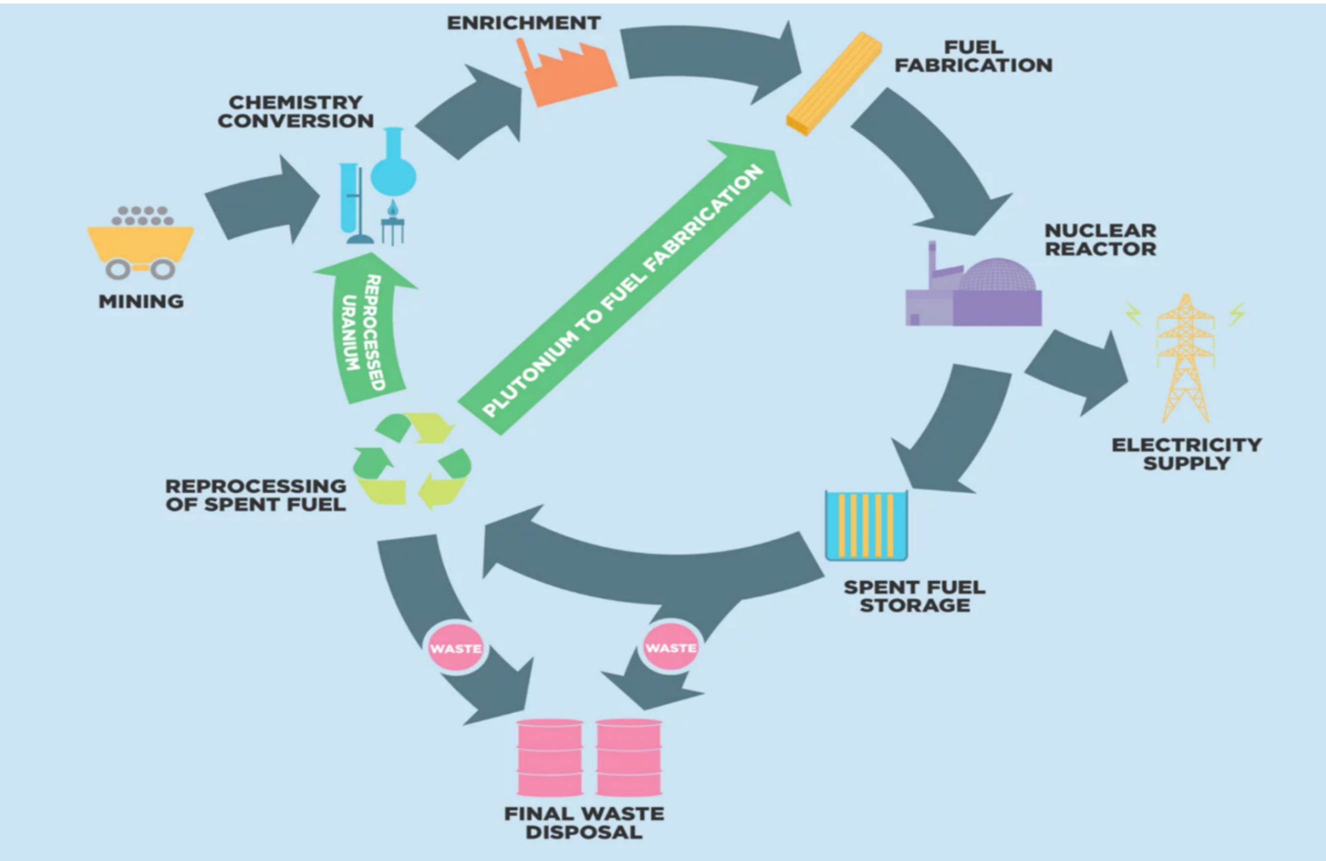
Alex Langton, Kate Taylor and Dan Whittaker

The climate crisis poses an unprecedented threat to humanity and, without a rapid switch from fossil fuels to low carbon methods of energy production, could lead to catastrophic global effects.[1] To meet this seemingly insurmountable challenge, the UK has pledged to achieve net zero carbon emissions by 2050.[2] In pursuit of this target, the UK government recently approved the new Sizewell C reactor, with a further eight nuclear reactor final investment decisions promised by 2030.[3] Laid out in its British Energy Security Strategy,[4] the UK government has a stated ambition to realise 24 gigawatts (GW) of nuclear power generation by 2050.

This significant increase in nuclear investment will necessarily produce more 'spent' nuclear fuel.

This presents, therefore, an opportunity to design and adopt a through-life-cycle approach to nuclear deployment and challenge the current government strategy of a 'once-through, no recycle' fuelling policy. This paper aims to explain the difference between open and closed fuel cycles, as well as outline the closed fuel cycle's similarities with the concept of a circular economy. The paper reviews different aspects of a closed fuel cycle in terms of sustainability, proliferation and economics. It then moves on to look at how closing the cycle could play a role in the UK's green transition to a more sustainable economy that is truly fit for the future without foreclosing on the options of future generations.

Figure 1: The Nuclear Fuel Cycle



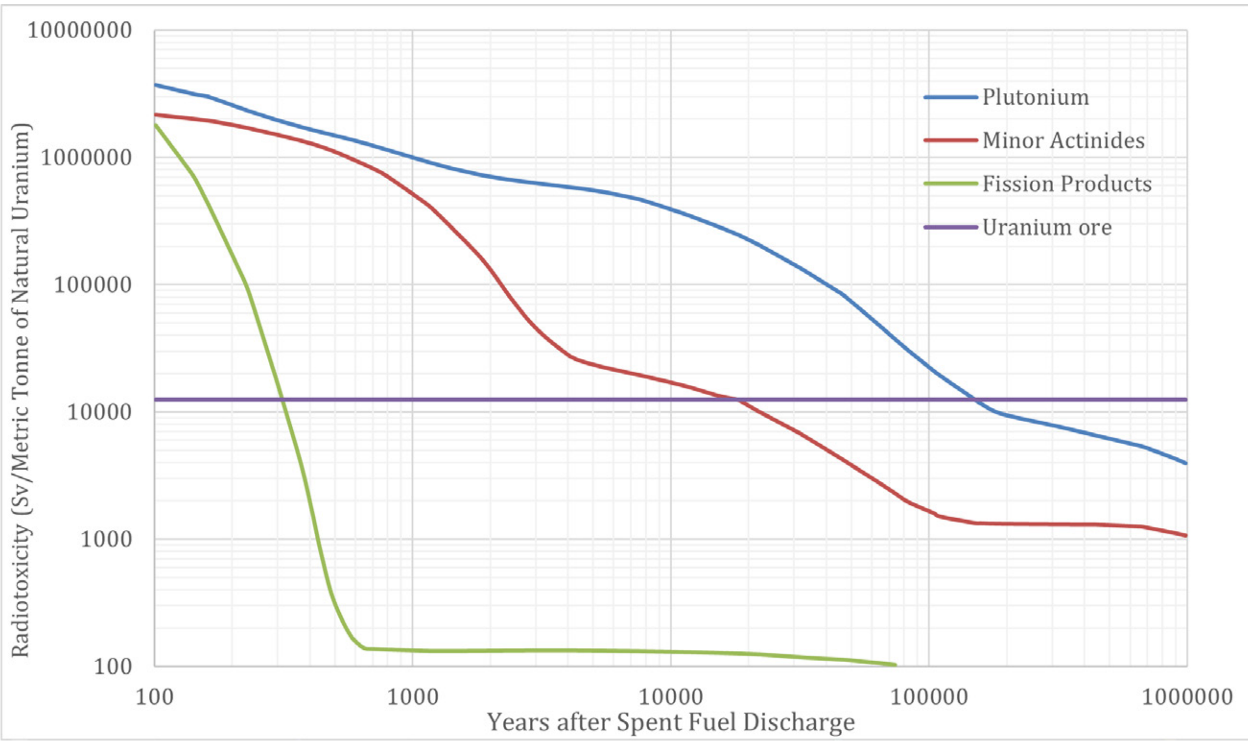
Source: Nuclear Industry Association, 'What is Nuclear Energy?', 2022, <https://www.niauk.org/industry/what-is-nuclear-energy/>, accessed 5 September 2022.

The nuclear fuel cycle (Figure 1) begins with the mining of uranium ore and its conversion into fuel. This process produces approximately 1 kg of uranium from 1 tonne of ore (assuming an initial uranium content of 0.10% in the ore). This 1 kg then undergoes enrichment to increase the proportion of uranium from 0.7% to between 3.5% and 5%, producing approximately 130 g of uranium ready for fabrication into fuel and then energy production.[5] Once this fuel has been used to generate electricity, it leaves the reactor as 'spent' fuel.

In an open fuel cycle, this spent fuel is stored, treated (encased in concrete) and eventually disposed of in a geological disposal facility (GDF); although there are currently no operating GDFs worldwide. In a closed fuel cycle, the spent fuel is recycled, removing the principal reusable components for reuse as fuel. The less prevalent remaining components – the fission products (FPs) – are treated by being converted into glass or encased in concrete and stored pending a GDF being made available. This process of recycling is commonly known within the nuclear industry as 'reprocessing'.[6]

Historically, the UK hasrecycled its nuclear waste by operating a closed fuel cycle. This was undertaken at the Sellafield site in Cumbria using the Thorp and Magnox reprocessing plants, commercial plants that processed nuclear waste to recover the uranium and plutonium for use as mixed oxide (MOx) powder. This was then converted into MOx fuel for domestic and international customers. Reprocessing has stopped since the closure of the Thorp and Magnox reprocessing plants. This decision was driven by a drop in demand for reprocessing due in part to lower uranium prices.[7] Sellafield is the site of the largest civil plutonium stockpile in the world (140 tonnes) and there is currently no final plan for its use or disposal.[8] Options include disposal in a GDF or its conversion into fuel for reactors. But until a decision is made, Sellafield is acting as its temporary repository.

Figure 2: Reasons to Separate Nuclear Waste ; the Radiotoxicity of Nuclear Waste Components Over Time

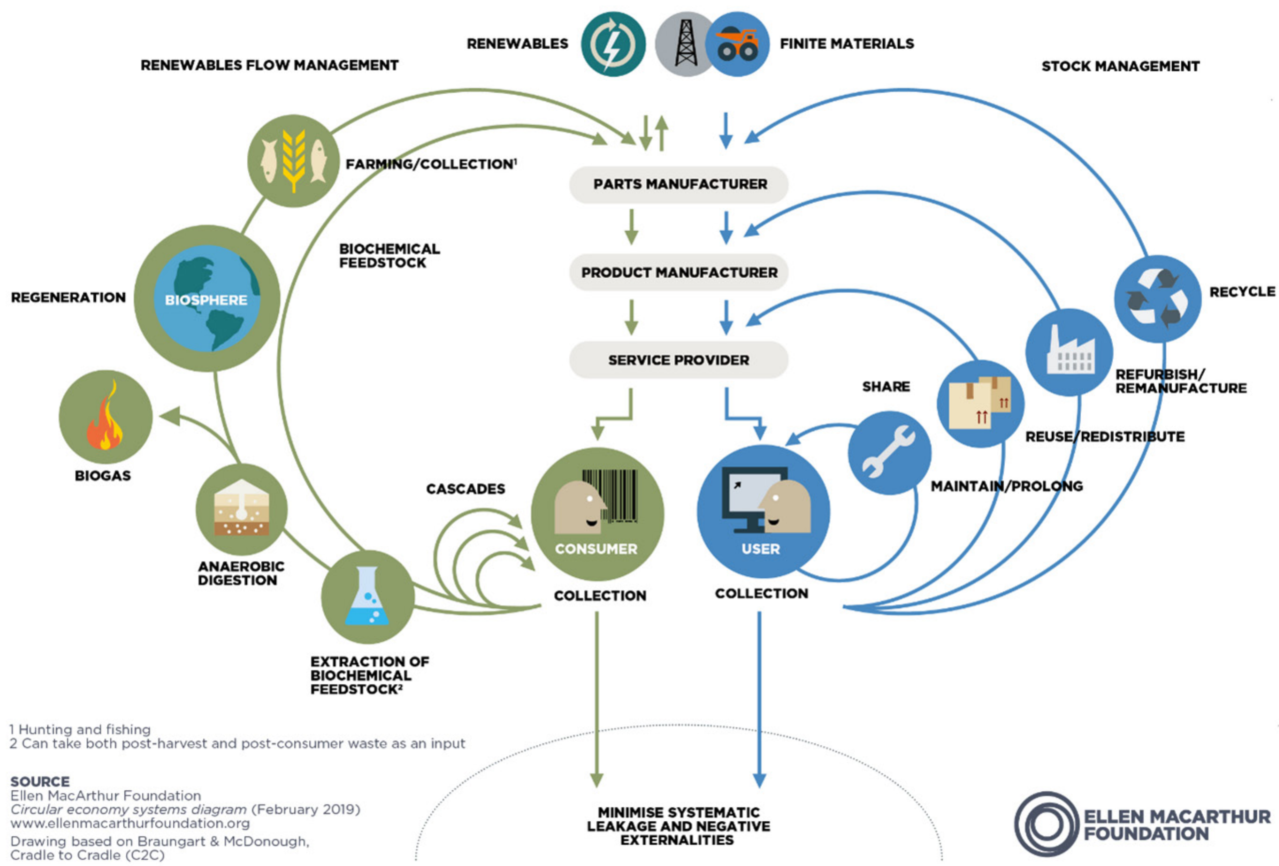


Source: Nuclear Energy Agency, Physics and Safety of Transmutation Systems: A Status Report *(Paris: OECD Publishing, 2006), p. 8.*

Figure 2 shows how the radiotoxicity of components of spent fuel changes over time. Plutonium, represented by the blue curve, takes over 100,000 years for its radiotoxicity to drop below that of natural uranium (purple line). For the minor actinides (primarily americium and curium), represented by the dark red curve, this time period is over 10,000 years. Finally, the green curve shows the fission products (principally isotopes of iodine and strontium), which reach natural uranium's radiotoxicity in less than 1,000 years.[9] Unlike the longer-lived elements (plutonium and minor actinides), fission products only need to be stored in a structure which must last several hundred years (rather than millennia). This is a much-reduced engineering challenge where humans have built several examples of structures that have lasted hundreds of years, such as castles and pyramids.

Future closed fuel cycles aim to recycle the plutonium and minor actinides into fuel in order to decrease the longevity of new waste material(s). This practice also decreases the quantity of waste going through more expensive waste treatment processes prior to storage, such as vitrification or hot isostatic pressing. This has the added benefit that without the heat load and neutron emission of plutonium and the minor actinides, packages can be stored closer together; inclusion of these varieties would require spacing between waste packages to ensure adequate cooling (passive cooling).[10] These advantages of recycling ultimately decrease the burden on a GDF and thus on future generations.[11]

Figure 3: A Depiction of the Circular Economy



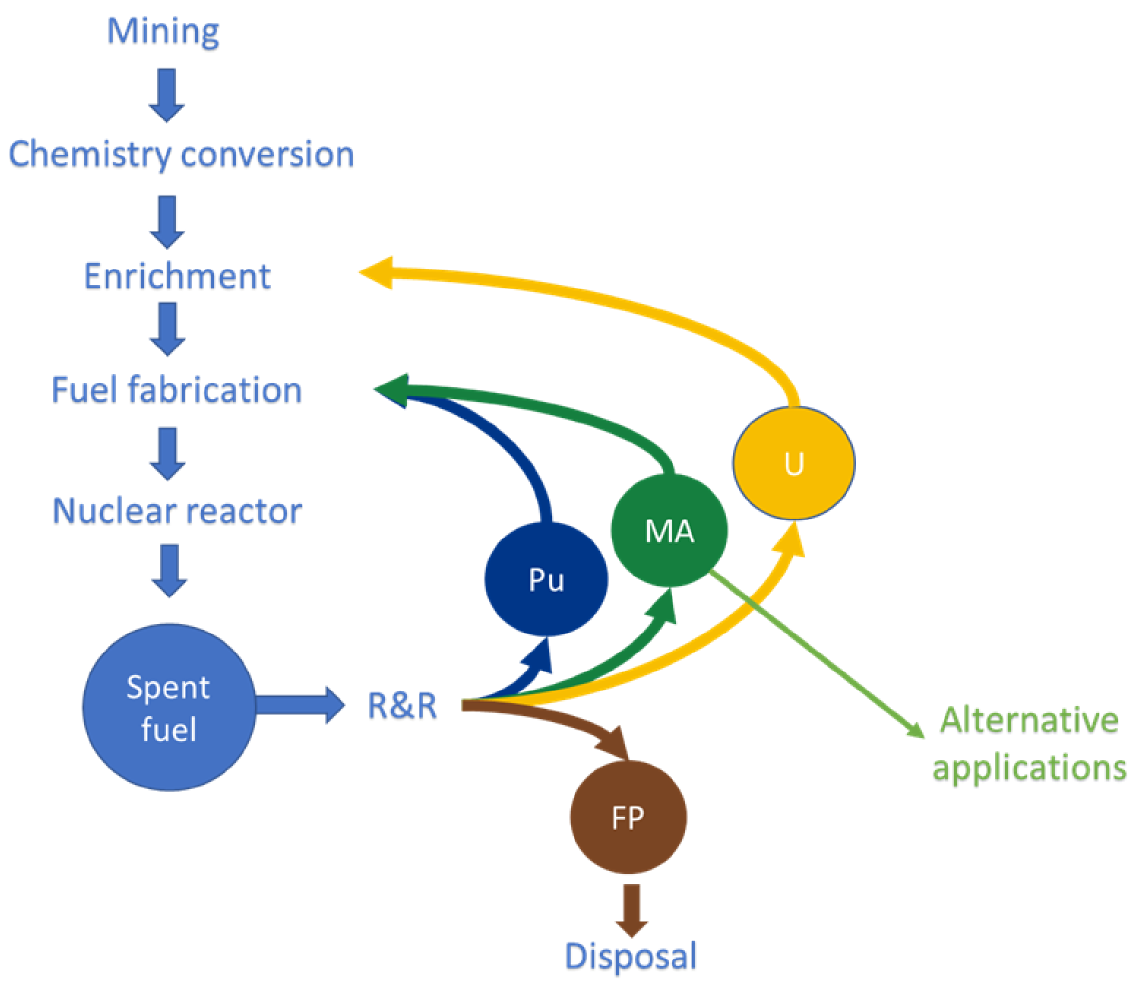
Source: Ellen MacArthur Foundation, 'The Butterfly Diagram: Visualising the Circular Economy', February 2019, <https://ellenmacarthurfoundation.org/circular-economy-diagram>, accessed 5 September 2022.

Circular Economy

The ‘circular economy’ concept (see Figure 3) describes how economies can adapt to become more sustainable and less environmentally impactful. Recycling was a key element in circular economy thinking from the very beginning of the concept’s development in the 1960s.[12] The main idea of a circular economy is to minimise the number of natural resources that must be extracted by feeding waste products back into the production route. This differs from current forms of waste management because reuse and recycling are proactively planned in at an early stage of conception, actively reducing the quantity of waste produced from the start rather than retro-fitting.[13]

In the context of the fuel cycle, the natural resource is uranium ore. By mass, the majority of nuclear waste is uranium.[14] Although the isotopic composition of the recycled uranium contains less fissile material than that of natural uranium, the inclusion of plutonium in MOx fuel results in extra neutron emissions, which can sustain the nuclear chain reaction.[15] Thus, spent fuel (the uranium and plutonium) can be fed back into different stages of the fuel production process to create MOx, or minor actinides can be used to generate fuel for a burner reactor (a special type of reactor that can process a wider range of nuclear material other than uranium/plutonium and which can therefore act as a waste disposal route for minor actinides, see Figure 4).[16]

Figure 4: Nuclear Fuel Reprocessing as Part of a Circular Economy



Source: Author generated.

Sustainability

The application of circular economy principles to the closed fuel cycle can improve its sustainability. Through proactive resource management, the amount of raw uranium ore required by the system can be reduced by increasing the amount of nuclear waste that is recycled into fuel. This allows a reduction in the demand for environmentally damaging mining operations.[17] Mining for uranium is currently done through open cast/pit or leach mining. Both methods have involved large-scale damage to local ecologies.[18]

As discussed above, the quantity (and longevity) of output waste is also reduced, easing the demands on GDFs.[19] This could mean fewer GDFs are required even if the scale of nuclear power output is increased. Given public sensitivity over GDFs,[20] this could have significant positive benefits on the general acceptability of a large nuclear energy programme.

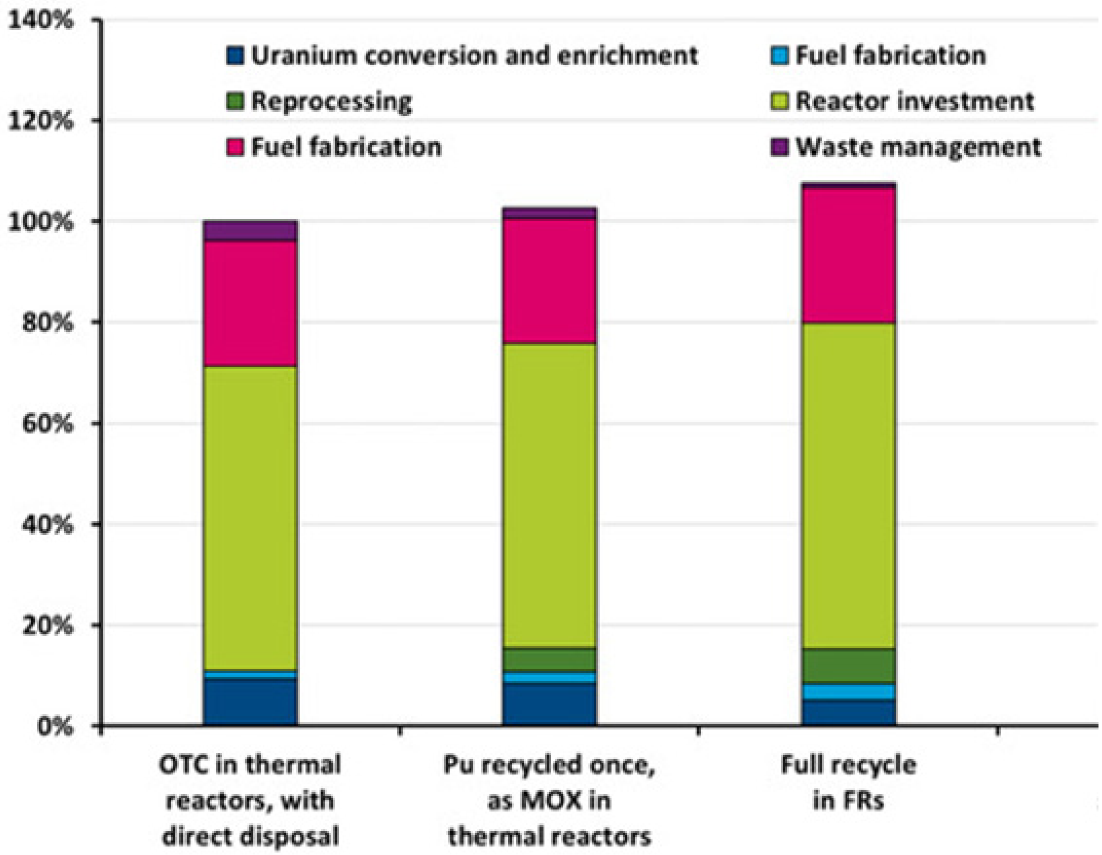
A closed fuel cycle would also extend the longevity of current uranium stockpiles, which are predicted to come under strain by the end of the 21st century if the UK and other countries, pursuit of net zero continues with open fuel cycles.[21] The depletion of these stockpiles could result in a similar scenario to the current gas crisis, as the UK relies on imports of uranium ore to produce its uranium fuel. A closed fuel cycle mitigates this by increasing the sustainability of nuclear power in the long term in a similar way to how the low carbon credentials of nuclear power increase the overall sustainability of the broader economy.[22]

Proliferation

One of the arguments against closing the fuel cycle is that it increases proliferation risk by making it easier to separate out fissile materials for use in nuclear weapons. For this reason, much research in the UK (and internationally) has focused on improving reprocessing technology to prevent the formation of a pure plutonium stream. Indeed, the recent Advanced Fuel Cycle Programme (AFCP), part of a £46-million investment by the UK government, focused heavily on this.[23] An explicit aim of the AFCP is to alter the chemistry involved in reprocessing, such that rather than producing pure plutonium it instead produces a mixed uranium/plutonium product, further reducing the downstream steps required to manufacture new fuel. This increases the barrier(s) to proliferation and, when coupled with other advances achieved through large-scale investment in reprocessing plants (such as online monitoring and real-time analysis), can very much change the nature of conversations around recycling nuclear fuel in the 21st century.

These improvements could be further improved by the use of 'fast' reactors (so called because they use a different neutron energy spectrum to conventional power reactors). Depending on how they are operated, such reactors are capable of 'burning' the long-lived actinides and/or producing more fuel for conventional power reactors. By reprocessing the waste products it is possible to separate them out into distinct waste groups, allowing for targeted waste strategies for each group, such as using burner reactors (minor actinides) or making MOx fuel (uranium/plutonium). This also means that the remaining fission products can be incorporated more compactly in a glass product rather than encased in concrete. Therefore, this becomes a trade-off in proliferation risk, with a shorter-term increase due to more active fuel and waste movement in exchange for a longer-term reduction in proliferation risk as the UK uses up more nuclear material in reactors and reduces the quantity of waste awaiting/requiring long-term disposal.

Figure 5: Relative Costs of Nuclear Fuel Cycles



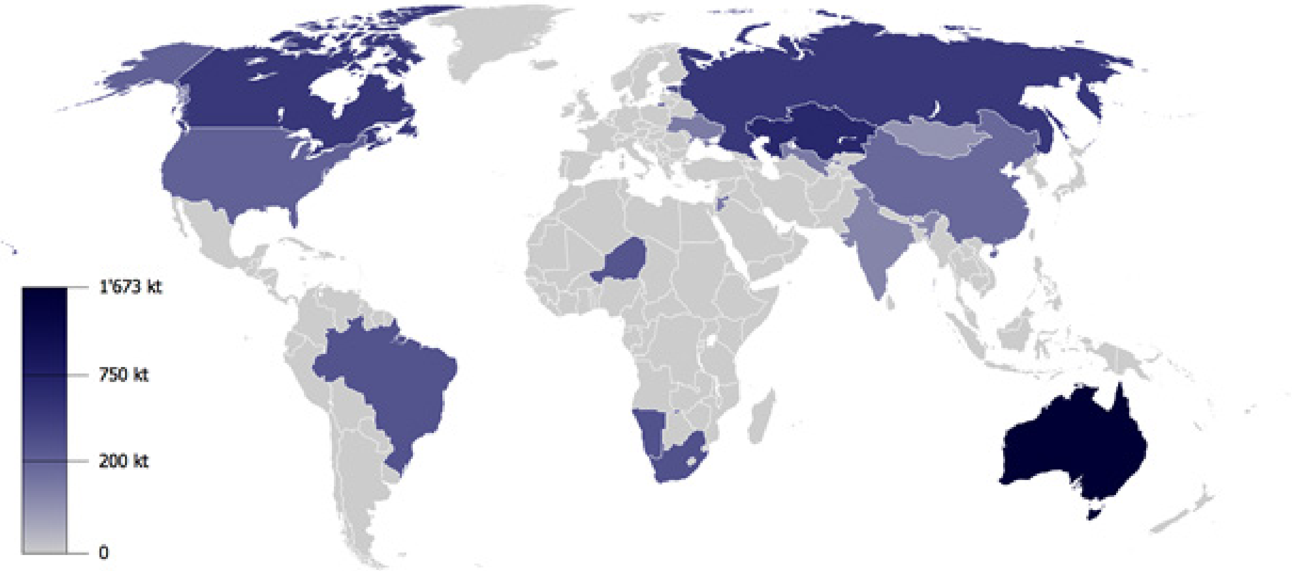
Source: R Taylor et al., 'A Review of Environmental and Economic Implications of Closing the Nuclear Fuel Cycle–Part One', Energies (Vol. 15, No. 4, 2022).

Economics

The bulk of the cost of implementing a nuclear fuel cycle, whether open or closed, is dominated by the costs of the reactor, rather than by the front-end (mining/enrichment/fabrication) and back-end (recycling/waste-disposal) fuel cycle costs. To allow comparison between different energy generating options, they are all normalised using the Levelised Cost of Electricity (LCOE) measure. The LCOE allows comparison of the capital and operational costs of different electricity generating technologies (see Figure 5). Treating an open fuel cycle as the baseline with 100% LCOE, the relative increase in LCOE when converting to a fully closed fuel cycle is around 8–9%. This is a relatively small increase for all the benefits stated. 'Reactor investment' (Figure 5) is in fact mostly a result of servicing the finance required for the capital outlay of the build (interest on loans).

Figure 6 shows the worldwide distribution of known uranium reserves in 2010. It shows that Europe, and specifically the UK, has no uranium reserves. The UK is therefore reliant on uranium imports to make its nuclear fuel. It is thus clear that the relatively small increase in costs associated with a closed fuel cycle produces another economic benefit in the form of security of supply; by committing to a closed fuel cycle, the UK can convert its nuclear waste into nuclear fuel, effectively creating a local supply.

Figure 6: Global Uranium Reserves in 2010



Source: Wikipedia, 'List of Countries by Uranium Reserves', July 2022, <https://en.wikipedia.org/wiki/List_of_countries_by_uranium_reserves>, accessed 5 September 2022.

This builds resilience into the energy system, a current topic of discussion in the context of the energy crisis.[24] Such resilience would also insulate the UK from future increases in uranium costs as the demand on uranium reserves rises. In addition, local supply would allow planning for reactor types and fuelling to be done years in advance of when they were required as the UK became self-sufficient. This is a very important point when you consider the lifetime of a nuclear power plant (40+ years).

Recommendations

As the UK transitions to a green economy where sustainability is a clear requirement, nuclear power is once again on the agenda, with the promise of eight new reactors. With more reactors comes more nuclear waste, and therefore this paper proposes that the topic of waste management is revisited. Any solution will require implementation at the national level, with a clear whole-cycle strategy led by the UK government. This strategy must incorporate sustainability in alignment with net zero, which could be achieved by applying the teachings of the circular economy. This paper lays out the reasoning behind (re-)closing the nuclear fuel cycle in the UK and the many and various benefits such a move would realise. The strategy would also require buy-in from the operating entities and designers, as reactor technologies and operational regimes will need to align with it. There is a clear opportunity present in the UK to take a more proactive approach to nuclear waste and to build resilience into the nuclear fuel cycle rather than simply focusing on the clean-up of legacy waste and using the burden of the past to colour the potential of the future.

The views presented in this paper are the authors' own and do not reflect the views of the Atomic Weapons Establishment, the National Nuclear Laboratory nor the UK government.

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IV. Getting Ready to Learn: Enabling the UK Nuclear Enterprise to Deliver Progressive Cost Reduction

Robbie Lyons

Nuclear power has assumed renewed prominence in the public debate over UK energy policy. As a low-carbon provider of baseload electricity, nuclear power is recognised for the role it can play in achieving the net zero goal.[1] Moreover, the heightened concerns for energy security driven by current geopolitical events increase the appeal of non-fossil-fuel-based energy sources with secure fuel supplies. This brings to the fore the widely recognised energy trilemma of needing a balance within the energy mix between low carbon emissions, security of supply and affordable costs.[2] In the case of nuclear power, high costs remain its weakness.

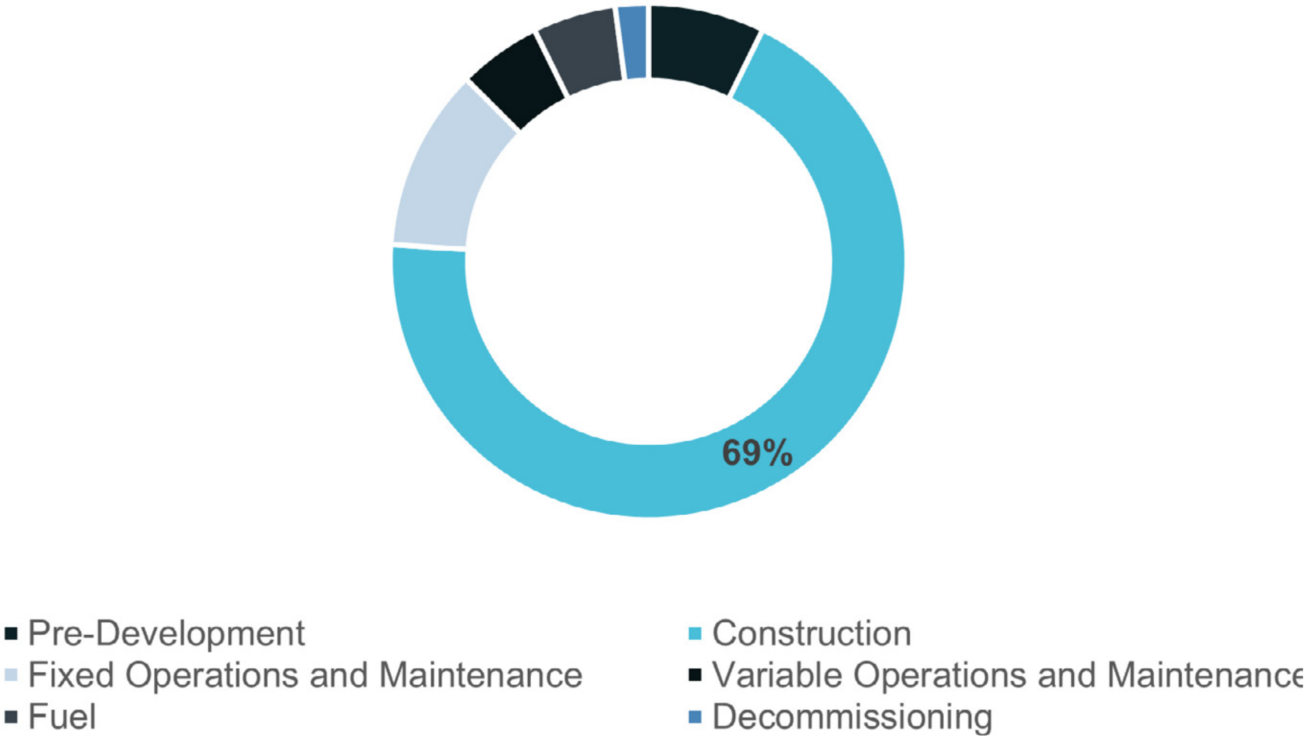
This paper considers the potential for small modular reactors (SMRs) to realise the goal of more affordable nuclear power. It presents an adapted summary of the relevant context and key findings from academic research by the author, in which SMR costs were modelled for different supply chain design and market demand scenarios.[3] The paper then explores the implications of these findings for industry and argues that concerted action by the UK nuclear enterprise is needed to deliver its cost reduction ambitions for small and large nuclear power plants alike.

Costs of Nuclear Power

The Levelised Cost of Electricity (LCOE) is the average cost over the lifetime of a power plant per megawatt hour (MWh) of electricity generated. LCOE values are commonly used as a basis for comparison of different electricity-generating technologies. If one considers LCOE data from the Department for Business, Energy and Industrial Strategy, nuclear struggles to compete on a cost basis with both gas-fired generation – the principal baseload alternative – and renewable energy options.[4] However, when making comparisons with the latter, it is important to be cognisant of LCOE's limitations: renewable technology, such as wind and solar power, suffers from intermittent supply owing to its dependence on weather conditions. The additional system costs of managing this intermittency are often not factored into the LCOE calculation, thus not providing a full account of the cost of electricity provided.

As shown in Figure 1, nuclear power's levelised costs are dominated by the capital costs of construction. Moreover, these capital costs in absolute terms are a huge barrier to getting new build nuclear projects started in the first place. This challenge has long been recognised by both government and industry, which is why one of the key elements of the 2018 Nuclear Sector Deal was the target of a 30% reduction in nuclear new build costs.[5]

Figure 1: Breakdown of Nuclear Power LCOE



Source: Department for Business, Energy and Industrial Strategy (BEIS), 'Electricity Generation Costs', November 2016, p. 27.

Small Modular Reactors: An Alternative Approach to Delivering Nuclear Power

SMRs are typically defined as having a reactor unit power of 300 megawatts or less, in contrast to current new build nuclear power stations, such as Hinkley Point C, which has a reactor unit power of approximately 1.6 gigawatts.[6] While reactor vendors have historically pursued more affordable nuclear power by making reactors larger in the pursuit of economies of scale, SMRs seek such cost benefits through production volume; specifically, three key principles are driven into the build process in order to bring construction costs down:[7]

1. **Standardisation**: by using a fixed design across multiple nuclear power plants, repeat engineering costs are removed and repeat production is enabled.
2. **Modularisation**: building the nuclear power plant out of modules manufactured off-site limits the on-site activity to site tailoring and module assembly, which brings significant labour productivity and schedule reduction benefits.
3. **Learning**: progressive reduction in cost is gained through learning, achieved through repeat production of standardised equipment and modules in a factory environment.

SMRs are also likely to benefit from lower financing costs, which are a significant component of the total capital cost of construction:[8] the anticipated shorter build times enabled by modularisation will allow less interest to accrue during the construction phase.

The build principles above are not exclusively applicable to small civil nuclear power plants; indeed, they are already applied to varying extents in large nuclear reactor construction, as well as in shipbuilding programmes. The benefits of standardisation and modularisation are well established in other industries, but cost reduction benefits from learning have proven to be particularly elusive in the nuclear sector. Moreover, while learning or experience curves are prevalent in aerospace and defence industry cost estimating, they are not always underpinned by robust plans to realise the benefits. As research has shown that production learning will be important to making SMRs cost competitive, this paper seeks to articulate the tangible steps industry must take to deliver learning.[9]

The Sources of Cost Improvement from Learning

Production learning is the well-documented phenomenon of the progressive reduction in unit costs as production experience increases. This has been codified through the definition of the learning or experience curve, which specifies a percentage reduction in unit costs for every doubling of production volume. This was first articulated by Theodore Paul Wright and has subsequently been adapted from forecasting average labour hours to total Nth unit production cost, as represented by Equation 1, in which 'n' is the production unit number and 'r' is the learning rate.[10]

Equation 1: Learning Cost Reduction Formulation

$$Nth\ Unit\ Cost = First\ Unit\ Cost \times (1-r)^{\ln(n)/\ln(2)}$$

For many energy technologies, this learning rate has been of the order of 20% or higher, whereas nuclear new build programmes have tended to achieve learning rates of the order of 3–5%; this rate will likely need to be significantly higher if the UK nuclear enterprise is to achieve the Nuclear Sector Deal cost reduction target.[11]

To determine how to achieve a higher learning rate, it is necessary to understand the sources that underpin the observed progressive cost improvement. Production learning can be broken down into three distinct elements, adapted from a summary by John M Dutton and Annie Thomas:

1. **Direct labour learning**: productivity improvement of direct labour, achieved by regular repetition of a standard activity.

2. **Indirect labour learning**: the optimisation of production processes, tools and workflow by implementing lessons learned by the workforce.

3. **Capital investment**: the improvement in production efficiency brought by investment in facilities and equipment.[12]

In pursuit of productivity benefits, SMR production will potentially implement advanced manufacturing and automated processes to replace manual tasks. It is therefore likely that indirect labour learning and capital investment will contribute more to aggregate learning cost reduction than direct labour learning. This paper therefore argues that the nuclear enterprise must engage in proactive planning and dedicated investment to deliver learning benefits.

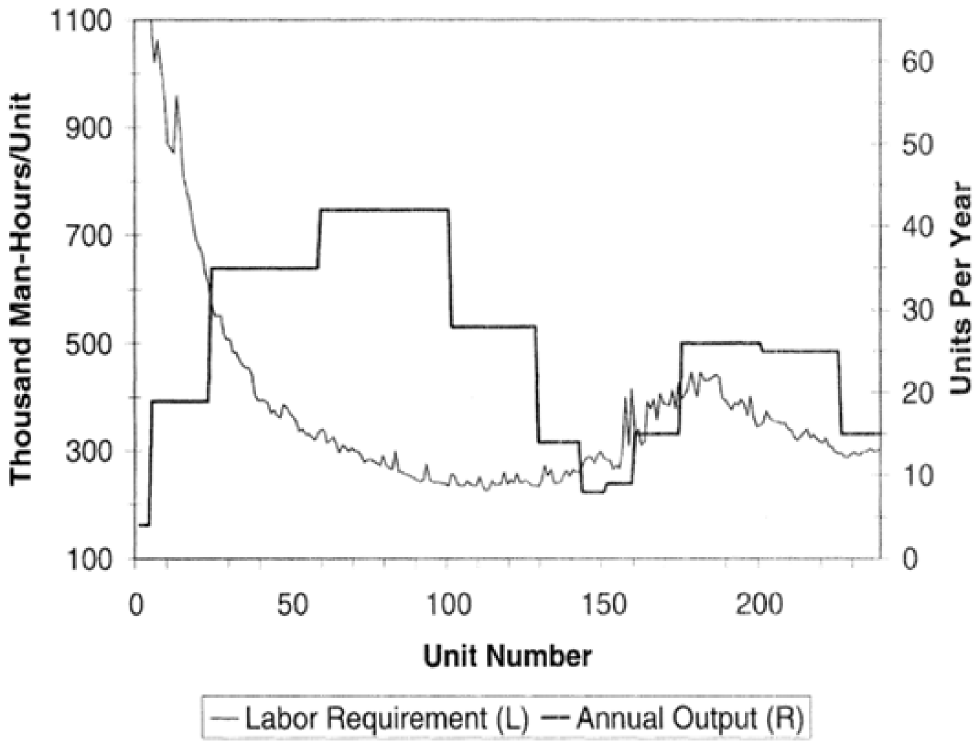
How to Drive Production Learning

Proactive planning will be critical to achieving learning because of the role of the production rate: specifically, the need for a sufficiently high and consistent production rate to create the conditions for learning. Regular, repeat production activities create the actual opportunities to learn from experience and then to apply that learning.

From another perspective, a high production rate helps to mitigate the risk of forgetting what has been learned from experience; while this is intuitive in the case of direct labour learning, it also has relevance for indirect learning. Figure 2 shows production data for one of Lockheed's commercial aircraft, the L-1011 TriStar. The thin line curving down initially on the left shows the production labour requirement, while the thicker, step-like line shows the annual production rate. The source paper considers the hypothesis that such increases in labour requirement following the decline in the production rate can be attributed to 'organisational forgetting', probably due to increased staff turnover or even a simple headcount reduction due to declining workloads. This indicates that skills and knowledge retention within the UK's nuclear enterprise will be critical to maintaining learning cost reduction benefits in the long term.

A high production rate also has a role to play in creating the confidence required for capital investment, the third source of learning cost reduction. The volume of production must therefore be aligned with capacity constraints over time to ensure a sufficiently high and consistent production rate.

Figure 2: Labour Requirement and Production Rate for Lockheed's L-1011 Programme



Source: C Lanier Benkard, 'Learning and Forgetting: The Dynamics of Aircraft Production', American Economic Review *(Vol. 90, No. 4, 2000)', p. 1039. Reproduced with permission of the* American Economic Review.

With the conditions established by a suitable production rate, indirect labour learning further requires both a learning culture and the ability to effect change within an organisation to ultimately realise learning benefits.

Cost improvement through indirect learning derives from ideas for change conceived by individuals involved in production. A learning culture, where these individuals feel empowered and encouraged to openly voice their critical observations and innovative ideas, is therefore essential. Organisations, as well as individuals, will need to take proactive steps to embed and maintain such a culture within their production environments. Further to this, the captured improvement ideas will inherently require change to production and business processes, whether small or large, which in turn requires dedicated capability and resources to implement. Consequently, organisations will need to invest in their ability to change, so that they can be assured of their ability to realise cost improvement benefits from learning.

Strategic Implications for the UK Nuclear Enterprise

Having established the need for proactive planning to maintain the production rate, and investment to establish both a learning culture and change capability, there is a case to be made for an aligned approach to nuclear new build across the UK nuclear enterprise, to an extent that may challenge conventional industry relationships.

Coordination of nuclear new build projects would support the balancing of production volume with capacity constraints to ensure a sufficient production rate across the nuclear supply chain and, in turn, optimal learning. This should be a consideration for the forthcoming public body, Great British Nuclear, which could have a driving role in bringing forward a series of new build projects.[13]

Notwithstanding the current ambition for nuclear new build in the UK, it is likely that certain sub-sectors will still have limited production volume. Knowledge-sharing and collaboration on production improvements between organisations in the supply chain would therefore be beneficial to maximising learning benefits and sharing the burden of the enabling change.

Finally, the broader issue of knowledge and skills retention within the UK nuclear enterprise will have a direct bearing on the sustainability of cost reduction. To maintain learning benefits for the long term, skilled individuals must be retained in the enterprise, both so that their knowledge is not lost and so that their experience can continue to be leveraged to drive further improvement. The skills challenges faced by the UK nuclear enterprise are well documented; and while retention has historically not been a particular issue for the sector, the drive for learning benefits will give it heightened significance.[14] Moreover, in the context of significant expansion of the nuclear industry, competition between organisations for skilled individuals risks fragmenting and diluting the knowledge accrued from learning. Greater career mobility across the enterprise, enabled by cooperation between public and private organisations, would support critical skills development and knowledge retention, while ensuring that learning benefits are maintained.

The contents of this paper are the personal views of the author, not those of PA Consulting nor its clients. The views presented here have been informed by discussions with the author's former PhD adviser, Tony Roulstone, and UK PONI mentor, Ed Read.

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V. The Role of UK Nuclear Power Generation in UK Energy Resilience

Lacey-Jo Marsland and Ben Goold

On 15 July 2022, the Met Office, the UK's national weather service, issued its first-ever Red Warning for 'extreme heat' in parts of England, with forecast temperatures of 40°C. Prior to July 2022, the record high temperature in the UK was 38.7°C, recorded in July 2019. The increased frequency, duration and intensity of extreme heat events over recent decades can be clearly linked to climate change and attributed to human activity.[1]

In October 2021, the UK government published a strategy to achieve net zero carbon emissions by 2050.[2] This strategy built upon 'The Ten Point Plan for a Green Industrial Revolution' from 2020, which highlighted 'delivering new and advanced nuclear power' as a means of generating new clean energy.[3] As part of this, the UK government has committed to a £385-million Advanced Nuclear Fund and a £170-million R&D programme on advanced modular reactors, among other things.[4]

This paper discusses the use of nuclear energy to build a more economical, self-sustaining future for the UK, focusing on the following three opportunities:

1. UK reliance on foreign fuel imports.
2. Sustainability benefits of using nuclear as an alternative energy source.
3. The potential use of advanced technology fuels (ATFs) to improve public perceptions of nuclear energy.

The UK is currently a net energy importer, relying on imports of foreign fuel for energy to power the National Grid and meet increased demand in the wake of the coronavirus pandemic.[5] These sources include countries with which the UK has strained diplomatic relationships, such as Russia. In 2021, fuel imports from Russia contributed to 4% of gas, 9% of oil and 27% of coal used in the UK.[6] Lack of access to Russian fuel imports in the face of sanctions is damaging the UK economy due to restrictions in energy markets, causing significant fuel price increases as other European countries compete for non-Russian fuel sources.[7] This is exacerbating the cost of living crisis currently being experienced in the UK.

The use of nuclear power in the UK would reduce UK reliance on foreign fuel imports and its vulnerability to energy market instability. While also being a comparatively clean energy source which could support the UK government's net zero target, nuclear power could allow the UK to be a sustainable and self-sustaining global leader.

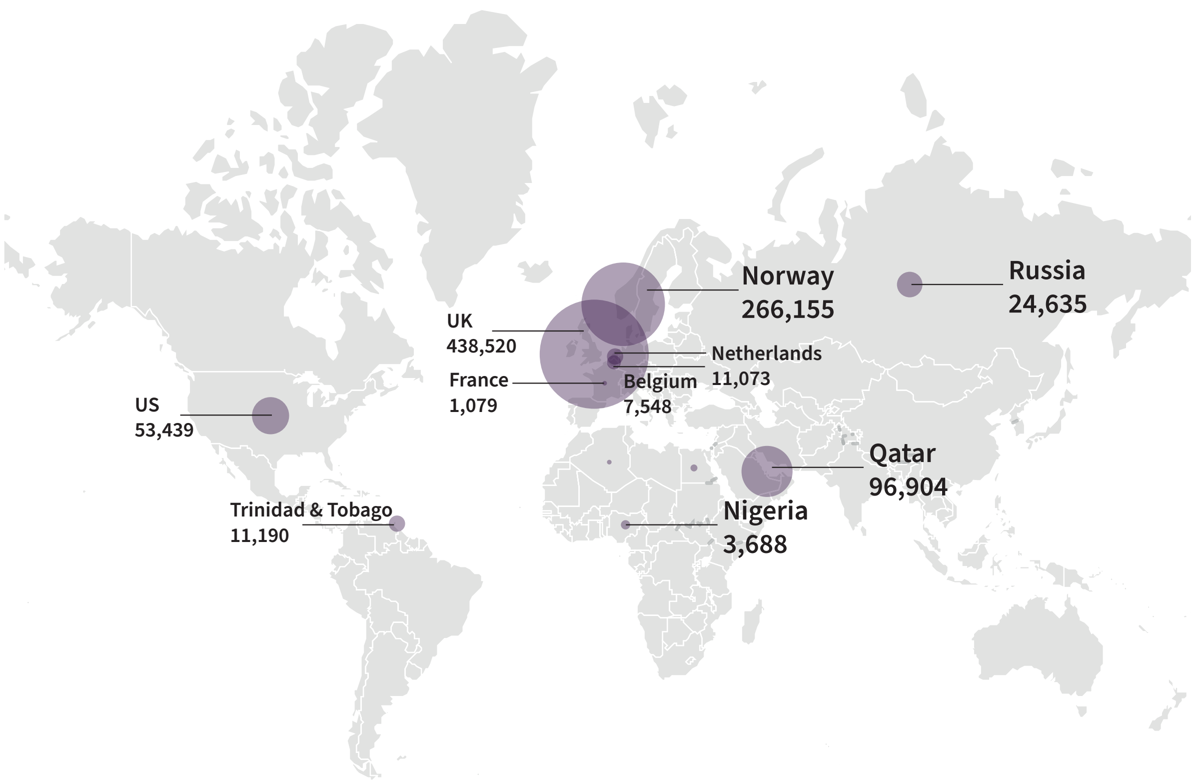
Despite the commitment of the UK government and the sustainability benefits of pursuing nuclear energy, however, public concern around the use of nuclear power remains strong.[8] Although public perception of nuclear power is slowly improving, there are concerns around some of the associated challenges such as safety, radioactive waste and high initial costs. The Department for Business, Energy and Industrial Strategy (BEIS) Public Attitudes Tracker shows that while 51% of people agreed that nuclear energy provides a reliable source of energy in the UK, only 38% agreed that nuclear energy provides a safe source of energy in the UK.[9] In recent years, there have been protests and interventions resulting from public safety concerns around UK nuclear power.[10] As safety is clearly a significant factor in the public perception of nuclear power, this paper will expand on public concern related to the safety of nuclear energy.

While the safe operation of nuclear power plants is a concern addressed in this paper, an aspect that still weighs heavily in public opinion is the safety of legacy waste produced by nuclear power generation.[11] The UK has set out proposals for a geological disposal facility(GDF) as a long-term solution to storing higher-activity nuclear waste.[12] However, this is ultimately a storage solution rather than an active disposal solution. Nuclear waste has previously been reprocessed by the UK to recover unspent fuel and reduce the total amount of waste produced by nuclear reactors. The UK currently has no operational reactors that run on reprocessed fuel[13] and as such the preferred option for nuclear waste is long-term storage.[14] This adds to public concerns around nuclear power.

UK Reliance on Foreign Fuel Imports

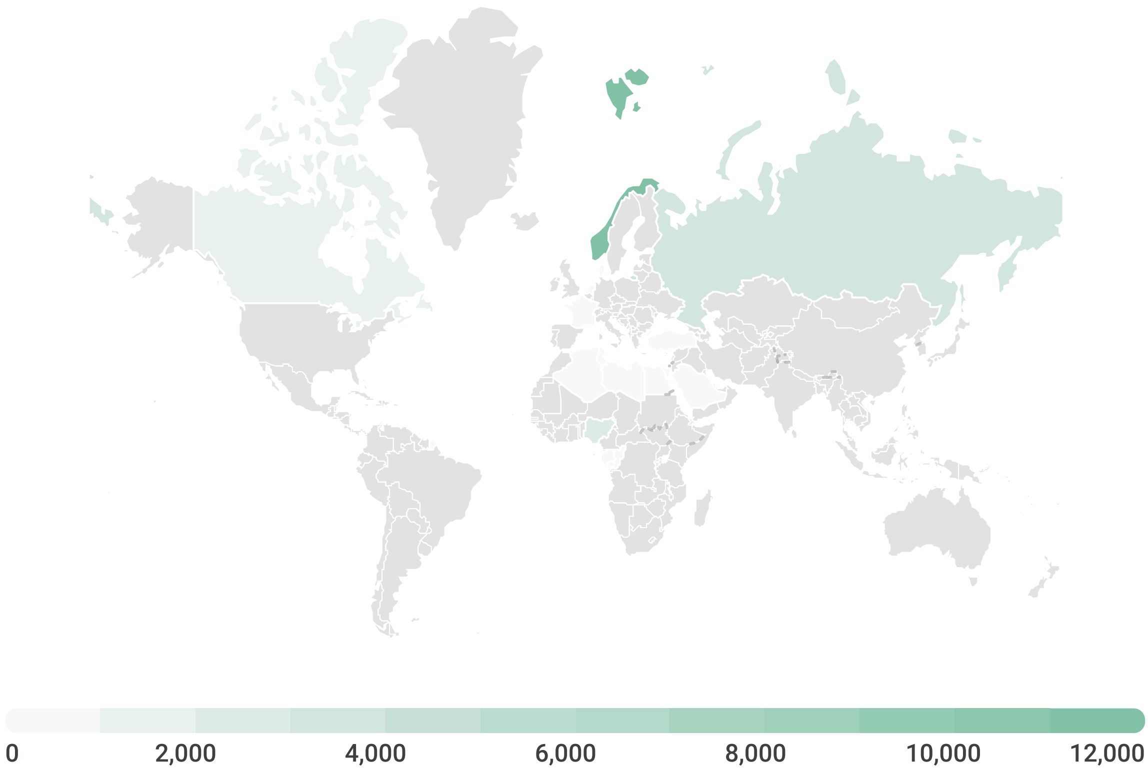
The two largest sources of UK energy consumption by percentage in 2020 were gas and oil; approximately half the UK's gas comes from the North Sea (UK Continental Shelf) and approximately one-third of imports come through pipelines from Norway.[15] The rest of the UK's gas imports come mainly in the form of liquefied natural gas (LNG) from places such as the US and Qatar.[16] The UK has only three LNG terminals and, as such, relatively little capacity to store LNG.[17] In order to maximise the benefits of LNG imports for the UK, additional terminals/storage infrastructure would likely be required. LNG supplies are also sensitive to global market fluctuations and are usually sold to those offering the highest price.[18] Figure 1 illustrates the diverse gas supply available to the UK in 2020, showing the gigawatt hours (GWh) of energy supplied by different countries.[19]

Figure 1: UK Gas Production and Imports 2020 in GWh



Source: Department for Business, Energy and Industrial Strategy.

Figure 2: Source of UK Crude Oil Imports 2020 (Thousand Tonnes)



Source: BEIS, 'Digest of UK Energy Statistics (DUKES), 2020', last updated 28 July 2022, Chapter 3.

The UK also has access to a diverse supply of crude oil imports, as illustrated in Figure 2.[20] The main source of crude oil imports for the UK has historically been Norway, with an increase in US imports in 2020. Approximately 13% of the UK's crude oil imports in 2020 came from OPEC (approximately 4.6 million tonnes); this value was approximately half that of 2019.[21]

Due to the diversity of fuel supplies available to the UK, it is highly unlikely that the UK would ever be completely isolated from all international energy sources. However, reliance on fuel imports leaves the UK vulnerable to global market fluctuations, as has been highlighted by the ongoing war in Ukraine.[22] Sanctions imposed on Russia have resulted in EU members relying on alternative fuel suppliers, restricting the market and increasing the demand for fuel from non-Russian sources.

When combined with the surge in demand for fuel following the coronavirus pandemic, the increased competition for non-Russian fuel sources in Europe has caused prices to skyrocket. For example, between May 2021 and May 2022 domestic gas prices in the UK increased by 95% and domestic electricity prices increased by 54%.[23] The use of nuclear power in the UK would reduce reliance on foreign fuel imports and consequently reduce vulnerability to energy market fluctuations. This presents a more economical, self-sustaining future for the UK in which a reasonable cost of living can be maintained.

Sustainability of Nuclear Power

Net zero is a scientific concept aimed at addressing the global warming and climate change challenges that pose the most crucial threats the world faces today.[24] These threats are pushing countries to consider generating electricity from clean energy sources. Under the Paris Agreement adopted in December 2015, 196 parties agreed to limit global warming to below 2°C while making efforts to limit it to 1.5°C.[25] Scientists have demonstrated that every one-year delay before reducing carbon emissions will decrease the remaining time available to reach net zero emissions by approximately two years (while keeping global warming below 1.5°C).[26]

The leading cause of global warming is carbon emissions from fossil fuel consumption – emissions which increase in line with energy demand.[27] The International Atomic Energy Agency (IAEA) estimates that the production and consumption of energy are responsible for approximately two-thirds of total greenhouse gas (GHG) emissions.[28]

GHG emissions from nuclear and renewable energy sources are one to two orders of magnitude below emissions from fossil fuels.[29] Additionally, nuclear power production can be scaled to meet demand in the same way as fossil fuels; this cannot be achieved by most renewable energy sources such as solar and wind (for example, if energy demand increases during periods of reduced winds or solar irradiation, this gap cannot be bridged). Nuclear power can be relied on to fill the gaps where traditional fossil fuels are currently required, allowing the phasing out of fossil fuels, reducing the UK's GHG output and potentially contributing to the Net Zero target.

Table 1: Power Produced by Varying Fuel Sources

Material (1kg)	kWh
Coal	8
Mineral Oil	12
U-235	24,000,000

Source: European Nuclear Society, 'Fuel Comparison', <https://www.euronuclear.org/glossary/fuel-comparison>, accessed 24 August 2022.

Another benefit of nuclear energy, when compared with fossil fuels, is energy density. Table 1 demonstrates the difference in power that 1 kg of different fuels can produce in kilowatt hours (kWh). This shows that considerably less nuclear fuel would be required to produce the same power as that derived from traditional fossil fuels. A nuclear fission event in a reactor produces approximately 193 megaelectronvolts (MeV) of energy; 1 kg of nuclear fuel, therefore, provides an energy density of approximately 80 million Joules per kilogram (J/kg).[30] The high energy density of nuclear power could provide a number of benefits to the UK, should this be pursued further. First, the UK is a small island nation; the space required for solar or wind farms to generate equivalent power to fossil fuels would be impractical and far less space would be required to generate the equivalent energy using nuclear power. Second, although it is acknowledged that the UK has no uranium mines and would likely rely on imports from established trade partners (such as Australia), the high energy density means smaller quantities of nuclear fuel (compared to fossil fuels) would be required, so imports would be less frequent and the UK could be less vulnerable to energy market fluctuations.

Advances in Nuclear Power

UK nuclear power projects have historically come in over-budget and over-time,[31] partly due to the stringent safety measures that are required, as a severe nuclear accident could have catastrophic consequences given the population density of the UK. The perceived high costs of nuclear power can deter potential investors and put governments under pressure, potentially leading to the cancellation of projects.

A loss of coolant accident (LOCA) is a well-studied failure mode of a nuclear reactor.[32] The loss of coolant to the reactor core means that the heat produced by radioactive decay is no longer moderated, causing an increase in reactor temperature. The water within the reactor turns to steam, which in turn reacts with the Zircaloy cladding. This exothermic reaction further increases the reactor temperature until the fuel rods melt down and containment is lost.

ATFs are alternative fuels or fuel claddings which aim to improve a reactor's response to a LOCA. In traditional reactors, uranium dioxide (UO^2) pellets are stacked vertically and then clad in a zirconium alloy to create a fuel rod. ATFs generally maintain UO^2 but can be doped with a ceramic or other materials; the claddings are made of materials which prevent the zirconium–steam reaction from progressing. The use of ATFs provides safety benefits in the form of reduced fuel fragmentation and dispersion during a LOCA. Computational modelling has shown that use of these fuel claddings can prevent a LOCA from progressing to a nuclear meltdown.[33]

Westinghouse have developed the ADOPT™ fuel pellets[34] which are UO^2 doped with chromia and alumina. This reportedly provides benefits such as a higher burn-up and an increased density of fissile material, resulting in fuel with a longer life and greater energy output.

There are currently no ATFs in operational use, but Westinghouse, Framatome and General Electric are aiming to have them in service by 2025.[35] If they are successfully deployed, they could provide safety benefits and cost savings to nuclear power generation.

In conclusion, nuclear fuel can provide the UK with a reliable and resilient energy source. While the UK will continue to rely on other nations for raw fuel, these are nations with which the UK is likely to have positive relations for the foreseeable future.[36] This reliance would also be at a lower level than is currently experienced for fossil fuels, due to less raw material being required. Furthermore, this would protect consumers from sudden price changes.

Investing in nuclear power will reduce the UK's carbon emissions and go some way towards meeting net zero targets and addressing climate change concerns. Nuclear power generation in the UK has had a history of economic difficulties, but investment in ATFs can provide safety and cost benefits which alleviate some concerns around its use.

The views presented in this paper are the authors' own and do not reflect the views of the Atomic Weapons Establishment nor the UK government.

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VI. Are Nuclear Breakout Times an Effective Way of Measuring a Country's Proliferation Risk?

Lucy Millington

This paper examines the effectiveness of using the concept of 'breakout time' to measure a country's proliferation risk. It also suggests options that could be used to improve the accuracy of nuclear breakout time calculations. The term 'breakout time' refers to the timeframe required to produce enough weapons grade uranium to produce the fissile material for one nuclear weapon. This calculation helps to provide a quantitative estimate of a country's capability to produce the material for a nuclear weapon and is an important tool when making decisions about how best to limit or reverse a potential weapons programme.

What Are Breakout Times and Why Are They Used?

Breakout times (BoT) is commonly calculated based on the length of time it would take a country to produce 25 kg of weapons grade uranium (WGU), enriched to at least 90% U-235. This is believed to be a sufficient amount to produce a single nuclear weapon. It should be noted that the amount of material needed to 'break out' differs from the International Atomic Energy Agency's (IAEA) definition of a 'significant quantity'. A nuclear weapon may require more or less than 25 kg of WGU depending on the production process and on the amount of material lost when converting uranium hexafluoride gas into a form that is useful for weapons production.

The aim of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) is to prevent the spread of nuclear weapons and weapons technology. The five nuclear weapons states – China, France, Russia, the UK and the US – are officially recognised as possessing nuclear weapons under the treaty. Under the NPT, all parties, whether nuclear weapon or non-nuclear weapon states, can access the benefits of peaceful nuclear applications. Nonetheless, sanctions and safeguards exist to prevent the continued production of inappropriately enriched nuclear material. The IAEA is the organisation responsible for key nuclear verification responsibilities (Article III). BoT is a useful tool for informing appropriate measures to impede unwanted proliferation, as they provide a quantitative estimate of a country's capability and can add clarity to complex debates.

The most well-known example of the use of BoT is as part of the Joint Comprehensive Plan of Action (JCPOA), an agreement reached by the P5+1 (China, France, Germany, Russia, the UK and the US) and Iran on 14 July 2015. Under the JCPOA, Iran agreed to limit its sensitive nuclear activities in exchange for the lifting of the sanctions placed on Iran by the UN, the US and the EU. BoT was a key factor in the decision-making process for the JCPOA, with President Barack Obama's administration basing its negotiations on the goal of putting Iran at 'one year to breakout'. This was important to ensure that there was sufficient time for the international community to respond to any move from Iran to resume enrichment above the agreed level.

Limitations of Nuclear BoT

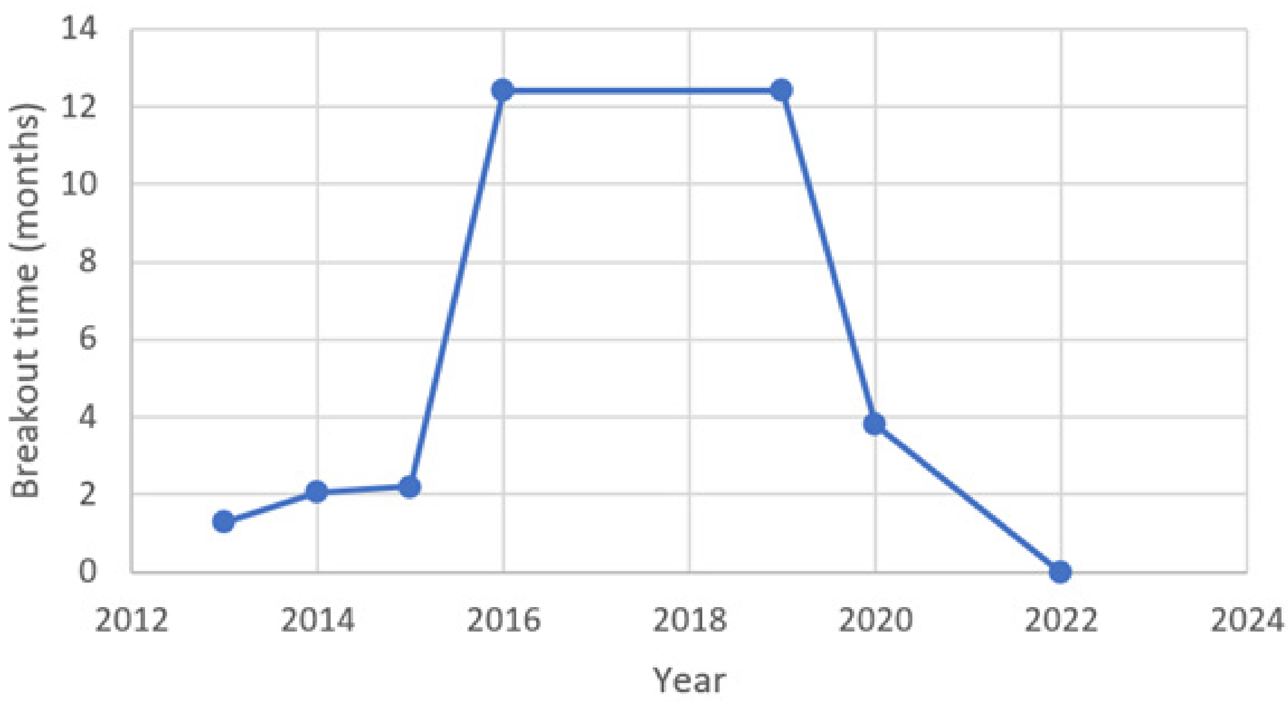
Although BoT provides a useful marker around which to frame sanction and safeguard decisions, there are drawbacks associated with its use. First, while BoT is designed to measure technical capability, it cannot capture strategic intent. A country's capability to enrich nuclear material does not necessarily imply it has the intent to produce a nuclear weapon. An example of this is Japan, the only non-nuclear weapon state in possession of a full nuclear fuel cycle. While

Japan could possibly produce the enriched material required for a nuclear weapon in a short timescale if desired, the international community is relatively unconcerned about Japan pursuing a nuclear weapons programme, even though Japan's BoT would be reasonably short. Japan has a comprehensive safeguards programme, and a strong negative public and political position on the issue of nuclear weapons ownership. Therefore it does not pose the same perceived threat as Iran, for example. This highlights the importance of putting BoT into context and considering them alongside additional factors that would signify that a country wishes to pursue a weapons programme.

Figure 1 shows the variation in Iran's BoT as calculated by the Institute for Science and International Security (ISIS) over a decade. Despite the fact that experts have estimated a variety of different BoTs over many years (often below 12 months), Iran has not yet produced a nuclear weapon. This reinforces the issues associated with quoting BoT values in isolation.

In addition, the output of BoT calculations relies greatly on the accuracy of the input data. Different parties calculating a BoT will have access to different sources of data, and their respective calculations might therefore be very different. There have been numerous debates about the correct way to calculate BoT, with experts from ISIS and the International Institute of Strategic Studies often quoting different values. Problems can arise when entering discussions about imposing safeguards and sanctions, as different parties may be working from different assumptions, making it more difficult to reach a unanimous decision.

Figure 1: Variation in Iran's BoT Between 2013 and 2022



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Finally, BoT calculations do not include the other aspects of nuclear weapons development. BoT is an estimate of a country's capability to produce the material required for a nuclear weapon, but it does not provide any information about the rest of the country's potential weapons programme. A country with a mature weapons programme (for example, sufficient explosives technology and an advanced missile programme) will have the same BoT as a country with the sole capability of enriching material, and yet the threat it poses in terms of proliferation is very different. This is because the weaponisation timescale will be much shorter for a country with a mature programme, reinforcing the importance of using BoT in the appropriate context.

Benefits of Nuclear BoT

Conversely, there are also many benefits to be derived from using BoT to measure proliferation risk. First, producing nuclear material is a significant step in weapons development. Although a BoT calculation does not include other aspects of a nuclear weapon programme, it is still an important value to calculate. The production of sufficient fissile material for a weapon likely indicates that a country has intentions of pursuing weapons development.

Second, the factors used in a BoT calculation are simple to estimate, given access to accurate data. The calculation includes variables such as the number of centrifuges, their type and configuration, and the current size and enrichment level of the uranium stockpile.[1] With access to the right information, these are all values that are not open to interpretation and therefore provide a valuable, objective measure of proliferation risk.

Third, if use of the BoT measure in its current form was discontinued, a suitable alternative for measuring proliferation risk would need to be identified. Modifying the BoT calculation to encompass other factors in weapons development would make the process much more complex and ambiguous than it currently is.

Recommendations for Improvement

This paper collates several options that could be used to both improve the accuracy of BoT calculations and to promote discussion about potential routes of advancement.

One method would be to incorporate political factors into the BoT calculation. A BoT accounts solely for a country's technical capability to enrich nuclear material, and do not refer to a country's intent to do so. The political will or desire to produce nuclear material would be difficult to quantify and would need to consider the political landscape of the country in question as well as that country's perception of the threat it is under. If this could be quantified it could be used as a weighting factor, where a higher degree of political will to produce nuclear material would decrease the BoT. This would prevent two countries with equal technical capabilities – but different intentions – from having the same BoT value. In discussions about safeguards and sanctions it would be informative to include both the traditional BoT and the 'BoT with intent' measure to help form a richer picture of the threat posed by a given country. Although this would be a difficult task, it could be possible through methods such as the Bayesian analysis of political will.[2] This would allow unknown variables to be treated as probability distributions and could add another level of confidence to BoT.

Another option would be to include other aspects of weapons development in the BoT formula. This would require extensive nuclear weapons knowledge and would produce a new measure that is no longer a BoT in its current form, but which would be a move towards calculating weaponisation timescales. The maturity and quality of other components of nuclear weapons, for example explosives technology, would be difficult to assess as, unlike nuclear material, they do not produce distinctive radiation signatures. Furthermore, the variety of different types and amounts of explosive that can be used in a nuclear weapon makes threat determination and programme maturity difficult to estimate. If such a formula was successfully developed and implemented, it would add depth and context to the traditional BoT value. A formula like this could be made possible via the investigation of factors, such as a country's resources, the output of its technical research, its budget, and its number of competent scientists. All these aspects could indicate the likelihood of a country possessing mature weaponisation technology.

A final suggestion is the analysis of historical BoTs. This would involve looking at the timescales on which other countries that have developed nuclear weapons have progressed their programmes. However, there are only 10 countries that have produced (or are believed to have produced) nuclear weapons, so the data pool is limited.[3] It is therefore unlikely that any of these historical BoTs will be comparable to the country for which the BoT is required (Iran, for example). In addition, five of these countries have programmes recognised under the NPT and were therefore not attempting to develop weapons covertly or while subject to sanctions and international condemnation. This affects the relevance of this data, as BoTs are currently used for countries that are racing to produce material for a weapon in contravention of the NPT. A larger pool of BoT data would be required to predict trends and draw statistically significant conclusions from the data. Due to the sparsity of the available data this is not likely to be a viable option.

Conclusion

It is important to have meaningful and accurate methods for assessing a country's proliferation risk. Preventing unwanted nuclear proliferation requires careful and thoughtful political discussions, and therefore it is of paramount importance to ensure that accurate data is being used. In the negotiations leading up to the agreement of the JCPOA, BoT was repeatedly used as a metric for assessing the success of the outcomes. Ensuring that a BoT is calculated in the most accurate way possible promotes well-informed discussions and the implementation of appropriate sanctions or safeguards. The primary example here is the slowing of Iran's proliferation progress as a direct result of the use of BoT.[4]

The effectiveness of BoT for measuring a country's proliferation risk is a contentious discussion which depends on a wide range of circumstances. While a BoT provides a good tool for assessing the severity of sanctions to impose on a proliferating country, they are only useful when contextualised, and cannot be the sole decision-making component. The BoT can vary considerably depending on the experts' input and the level of information available to those experts. This can cause conflict when working to form a unanimously agreed safeguard or sanction. However, the intended use of the BoT is also important: if the BoT is being used to drive political action, a less accurate value can be acceptable if it prompts key decision-makers to begin appropriate discussions to limit proliferation.

While BoT is only currently being used for Iran, in the future it might be used for other states that seek to proliferate. More countries may pursue such proliferation strategies, especially given the Russia–Ukraine war providing a modern-day example of a nuclear weapons state threatening to use its arsenal, the ever-unpredictable North Korea and an increasingly aggressive

China.[5] With the use cases of BoT potentially increasing, it is important that the measure is well understood and that it is not miscommunicated or confused with weaponisation timescales. A BoT has a significant role to play in the nuclear proliferation narrative, but caution should be taken when using them in isolation as an indication of a weapon programme's maturity.

This paper does not represent the views of the Atomic Weapons Establishment, the Ministry of Defence nor the UK government.

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VII. Unconventional Uses: Exo-Planetary Applications for Nuclear Detonations

Josh Mulholland, George Parkes, Josh West, Elliot Short and Alasdair Kay

The history of nuclear detonations is fraught with horror and controversy, even though their use is not limited to weaponisation. Since their conception, consideration has also been given to how nuclear detonations can be used in a peaceful manner, and for the benefit of humankind. This is not just limited to detonations within the confines of Earth. There has been research into exo-atmospheric nuclear technologies in the past, but the use of nuclear detonations specifically has received minimal consideration since the introduction of the Partial Test Ban Treaty in 1963,[1] as the prohibition of nuclear explosions in outer space means that research into alternative (non-treaty-breaching) methods has had a higher priority.

This paper explores three potential applications of non-terrestrial nuclear detonations: planetary defence; interplanetary travel; and extra-terrestrial terraforming. All of these use cases require significant amounts of energy, and in the absence of new exotic technologies, nuclear detonations appear to be the existing solution most capable of meeting this threshold in the future, albeit with significant drawbacks. The paper examines previous work in these areas, looking at how nuclear detonations can be exploited. Despite policy and technical issues, there remain arguable benefits to further theoretical research and innovation in these areas, as well as a need for deeper discussion about the policy implications of doing such research. In addition to the violation of the aforementioned treaty, it should be noted that there are potentially significant and long-lasting negative environmental effects.

Although using nuclear detonation devices may also seem in breach of Article IV of the Outer Space Treaty,[2] it could be argued that these uses are not with the intention of weaponising space, and as such should be considered as part of the peaceful purposes not prohibited under the treaty. Article IX dictates that this would need to be performed as per the principle of cooperation and mutual assistance, and this would need to be considered, but the overall aims of benefiting humankind as a whole are aligned with the spirit of the treaty.

Planetary Defence

Nuclear policy addresses established terrestrial geopolitical threats, but threats from space can result in destruction and effects similar to – or well in excess of – nuclear weapons, albeit with a different probability of occurrence.

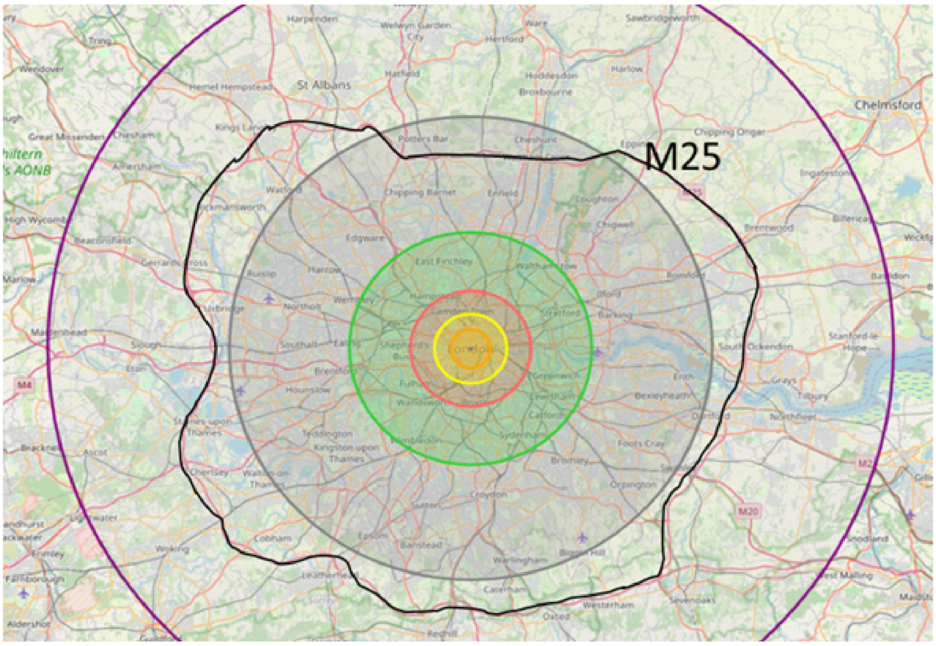
More than 1 million asteroids have been discovered in the Earth's solar system alone.[3] While most are not a threat (due either to their small size or having a trajectory that does not approach the Earth), the consequences of impact from a large asteroid could be dire. This threat will not change in the future, as it is a fundamental fact that collisions occur (every object in the solar system has the impact craters to prove this). For the purpose of comparison, it is worth noting that an asteroid the size of a house travelling at 30,000 miles per hour has the equivalent energy of the Hiroshima bomb, and the impact of a 140-metre diameter asteroid has the potential to obliterate a city (see Figure 1). Kilometre-scale asteroids, 877 of which NASA is tracking, are equivalent to 1 million megatons of yield and would likely cause an extinction event.[4]

Planetary defence is therefore a vital endeavour for the continued existence of humankind. Given significant advance warning, non-nuclear options could be used to create a small alteration to an object's trajectory. Such small, early alterations can propagate over years or decades to ensure that the object does not collide with the Earth. These options include low-energy kinetic impact solutions (such as the technology successfully tested in the Double Asteroid Redirection Test (DART) mission launched by NASA and APL in 2021)[5] or gravity resonance devices (using the same effect that creates the bands in Saturn's rings).[6]

Typically, large objects in space are identified early, but space is vast and there is a risk that there might only be a short period in which to act after objects are spotted (some objects are not spotted until after they have passed between the Earth and the Moon).[7] Additional risks come from extra-solar asteroids that only pass through the Earth's solar system once, and which do not have a regular orbit that can be tracked.[8] There is therefore a possibility that there could be insufficient time for lower energy options to be used. Nuclear technologies provide an alternative that could be used as a last resort to reduce the damage caused by a collision.

One solution could be to use nuclear-pumped lasers, similar to those proposed in the Strategic Defense Initiative's Project Excalibur, a research programme to develop an x-ray laser system as a ballistic missile defence for the US.[9] This approach could be useful against comets (and other celestial bodies that have significant water content), vaporising ice and creating a jet of continuous thrust. However, despite the benefits of speed-of-light engagement, the production of sufficient energy is difficult and success would still require early engagement. This technique would also be far less effective against asteroids of a stony/metallic composition.

Figure 1: Effect Circles of a 140-Metre Asteroid Impact on Westminster



Source: Asteroid Map, <https://asteroidcollision.herokuapp.com>, accessed 1 September 2022.

Key: Orange: crater, all living things die. Yellow: most living things perish, all buildings knocked over. Red: human skin may burn, infrastructure damaged, flying debris that could be fatal. Green: buildings destroyed, some clothing may ignite, heat and debris fatal to many. Grey: extreme heat, fatal to the elderly or those with health problems, buildings mostly stand, sound shockwave. Purple: ash and dust fallout, everyone in this region would see or hear impact.

Traditional nuclear weapons could also be used to have similar – albeit larger – effects, acting as a kinetic impactor and reducing the required lead time. However, there are still inefficiencies involved, and this technique is unlikely to be effective against particularly large threats or threats discovered late.

If an object is spotted late (with potentially only a year to engage), low-energy diversion tactics may not be possible. A viable alternative to reduce the damage caused by an impact might be to use a large-yield nuclear device.[10] Modelling predicts that a megaton device can be effective against asteroids under certain conditions.[11] Simulations show that for smaller asteroids (100 m or less in diameter) engaged at two months prior to impact, the impact mass of the object can be reduced to as low as 0.1% of its original level. For larger objects, engaged at six months prior to impact, this can still be reduced to 1% of the original level. This would result in the distribution of radioactive materials in space (potentially in close proximity to the atmosphere), which would potentially have long-lasting implications on human health, communications, and space travel. However, using nuclear detonations as a means of planetary defence against asteroids should only be considered as a last resort scenario. In these circumstances, this would be a justified risk relative to that of unmitigated and unfettered impact.

As an addition complication, the 'trolley problem'[12] would come into play here, as trajectories will change with the interaction. Policy considerations must therefore be given to the implications of a space-capable state using this method to prevent mass damage to their domestic population and infrastructure at the expense of a lesser impact on another (potentially unfriendly) state.

The potential implications for regional power dynamics should also be considered. The devastation caused even by a reduced damage impact could trigger a collapse of local governments. In unstable regions, this could leave a power vacuum for other local powers, paramilitary or terrorist groups to seize control of an affected region. Even for stable powers, the damage could impact critical military infrastructure, weakening them to the point where they would be vulnerable to opportunistic attack.

Nonetheless, planning for such events would allow the technology to be put in place and ensure time was not wasted in developing solutions, meaning that decision-making was less rushed and that technological capability would not be a limiting factor should an object be discovered with a short lead time.

Interplanetary Travel

December 2022 marks the 50th anniversary of the final Apollo mission: the last time human beings travelled beyond low Earth orbit (LEO) and set foot on an extra-terrestrial body. The limits of human biology in space environments and available spaceship propulsion technologies have made crewed missions beyond LEO since the 1960s space race unfeasible.[13] Nuclear pulse propulsion (NPP) is considered a potential solution to this problem by enabling faster and further travel within the limits of human survivability in space. This faster travel could also potentially outweigh the negative impact of extra radioactive material being introduced in the environment from such travel. However, significant additional work would be needed to fully assess the ongoing risk.

NPP uses the high yields of detonations to provide thrust, accelerating a spacecraft. There are two main concepts in this area, both involving a fuel pellet (consisting of a nuclear detonation device) and some propellant. The first approach is to direct the propellant forwards onto a pusher-plate shock absorber, imparting forward momentum onto the spacecraft. The second is to detonate the nuclear device within a reaction chamber and expel the propellant away from the spacecraft, similar to the way that propellant is employed in a conventional spacecraft but providing a much larger impulse.

NPP was first seriously considered by Project Orion, a 1950s–60s US feasibility study sing the first concept for crewed space travel.[14] The Partial Test Ban Treaty, the prioritising of the Apollo programme and the emergence of nuclear thermal engines meant that Orion never progressed beyond the theoretical design stage. Since Orion, designs have mostly been created for smaller unmanned probes as a proof of concept before scaling up to crewed spacecraft. The NPP systems have also moved on from the 'pusher-plate' concept to the 'expelled propellant' method.

Multiple future NPP concepts have been proposed, based on variants of terrestrial nuclear fusion reactor technology. These fall broadly into two categories: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). The simplified explanations of both of these involve triggering fusion by heating and containing the fuel pellet up to a plasma state, either through magnetic fields in the case of MCF, or with high energy particle beams in ICF.

A 2003 proposal for an MCF vehicle theorised a crewed return mission to Saturn's moon, Titan, in only 204 days.[15] It is worth noting, though, that this relied on significant progress in plasma confinement and high-temperature superconductor technology to come close to feasibility. Project Daedalus proposed an ICF-based propulsion system using electron beams to ignite and contain fuel pellets.[16] The NASA Human Outer Planet Exploration Group also explored a mixed ICF/MCF concept called magnetised target fusion.[17]

Research suggests that NPP can offer higher potential than other propulsion systems for enabling the crewed exploration of space. The challenges of developing the technology to increase feasibility are expected to be high, but many of these mirror challenges faced by the terrestrial fusion energy community. Enabling further NPP research can be used as an additional motivator to advance technologies of material sciences, power systems, plasma physics and superconductors, which could then provide further benefits to energy generation on Earth. Space exploration (and the subsequent potential for extra-terrestrial resource mining) could be a further driver for investment and research into this area, which would provide great benefit to humankind.

Extra-Terrestrial Terraforming

Terraforming is the (currently hypothetical) method of deliberately modifying the atmosphere (principally) of another planet so that it replicates the conditions of Earth to allow humans to survive. Harnessing the immense energy outputs of nuclear detonations to induce environmental alterations is not a completely novel concept; the US Atomic Energy Commission researched this through Project Plowshare between 1958 and 1975.[18] This looked at peaceful ways to use nuclear detonations on Earth to create such things as harbours, canals and mountain passes.

On a larger scale, beyond the confines of Earth, nuclear devices could also dramatically alter the atmosphere of other planets. Heat from nuclear detonations could be used to melt ice-caps and release water. On Mars, where there is an abundance of trapped CO2 in the ice-caps, the resultant rapid gas releases could also kick-start a greenhouse effect, potentially enabling the planet to warm to suitable life-preserving temperatures and creating a thicker Martian atmosphere, conducive to plant life. This would enable crop growth and oxygen production, to support human colonisation.[19] There are many widely acknowledged theories that nuclear detonations on suitable terrain could be used to raise dust and ground material into the upper atmosphere, blocking out sunlight and creating a 'nuclear winter' effect, facilitating planetary cooling.[20]

Of course, extra-terrestrial terraforming must overcome significant challenges. The ability to model the exact effects of such techniques is still a distant prospect, and accurately predicting the outcome of terraforming is currently a monumental challenge. There is also the issue of the sheer scale of such a project: the total number of nuclear detonations required to terraform a Mars-like planet is well beyond the current stockpile availability, the timescales over which detonations are required are immense, and hundreds, if not thousands, of generations are required for the terraforming effects to stabilise and the harmful radiological outputs to dissipate. Although these outputs will likely have dispersed in the geological timescales for the planet to become fully habitable, they could severely impact short-term Martian colonisation efforts. That said, it is an inescapable fact that, for the human race to survive into the distant future, at some point resource limitations will require humanity to spread out beyond the Earth, and any understanding of the role nuclear technologies can play in enabling this to happen will be of benefit.

Conclusions

Research has been undertaken on developing ideas about harnessing nuclear detonations for the benefit of humankind. There is no denying the very real hurdles that must be overcome to turn any of these ideas – which many think of as belonging in the realms of science fiction – into science fact. There are risks involved in transporting nuclear materials into space,[21] there are proliferation concerns if current non-nuclear states become involved in this research, there are policy concerns regarding nuclear weapon states using these as methods of force projection, which could be destabilising, and there are technological advances that need to be made in several fields.

However, there are also very real benefits to be derived from the exploitation of nuclear detonations in a peaceful manner beyond the confines of the Earth. As well as encouraging international collaboration in a similar manner to that achieved by the International Space Station, further research into these areas could drive technological improvements in other areas while also affirming humankind's ability to protect the Earth, explore strange new worlds, and expand civilisation's galactic footprint.

The purpose of treaties is to ensure the ongoing safety and security of human life. By considering nuclear detonations beyond the context of WMDs, research can further contribute to these goals, and as such it is time for policymakers to actively consider how states can pursue these ideas in a responsible manner.

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VIII. Understanding How Campaign Analysis, Open Source Intelligence and Emerging Monitoring Technology Impact China Strategy

Jamie Withorne

In June 2021, open source analysts used satellite imagery to reveal that China was likely constructing over 100 new ICBM silos near Yumen.[1] This revelation shocked international security experts across the globe, yielding extensive subsequent news media coverage and analysis. One month later, open source analysts at a different organisation used additional satellite imagery to show that China was constructing a second nuclear missile silo field in the eastern part of Xinjiang province and a third silo field at the Jilantai training site.[2]

While not directly referenced, these open source analyses influenced the November 2021 US Office of the Secretary of Defense's Annual Report to Congress on China's military developments, which explicitly states

> 'the PRC [People's Republic of China] is developing new intercontinental ballistic missiles (ICBMs) that will significantly improve its nuclear-capable missile forces and will require increased nuclear warhead production … The PRC has commenced building at least three solid-fuelled ICBM silo fields, which will cumulatively contain hundreds of new ICBM silos'.[3]

China later denied these claims.[4] Nonetheless, open source identification has evidentially shaped the 2022 US National Defense Strategy, which prioritises 'act[ing] urgently to sustain and strengthen deterrence, with the People's Republic of China (PRC) as [the] most consequential strategic competitor and pacing challenge for the Department [of Defense]'.[5]

While this latter example clearly shows that open source investigation can directly impact national strategy, little analysis has been devoted to examining this relationship in depth. For example, technology has often been assessed in traditional strategic analysis through gauged lenses of lethality and rapidity rather than in terms of monitoring or intelligence using surveillance and reconnaissance capabilities, such as publicly available satellite imagery. Moreover, little research has been dedicated to understanding the application of traditional campaign analysis methodologies to examining the relationship between open source intelligence (OSINT) and national security strategies.

Using illustrations from Chinese campaign analysis, this paper demonstrates how applying such methodologies can shed light on the ways OSINT impacts national security strategies. Specifically, this paper seeks to address the question: how does OSINT, enabled by emerging monitoring technologies, affect national strategy using campaign analysis methodologies?

By illustrating the relationship between OSINT and campaign analysis, using China as an example, this paper shows that emerging technologies such as publicly available satellite imagery can help facilitate the integration of higher-quality open source information into campaign analysis. Using such methodologies can in turn improve the understanding of adversarial posturing, yielding more tailored national nuclear strategies.

Conceptualising 'Technology'

This paper conceptualises technology as an intermediate variable that facilitates the analysis of military force and respective strategies, rather than as an independent variable that directly determines strategic success. Specifically, it considers publicly available satellite imagery technology as an example of characteristics associated with 'emerging' monitoring technologies. In this vein, such technology does not directly determine the success of nuclear strategy, but it can facilitate the analysis of force employment, which in turn shapes successful future strategies.

Satellite imagery has been in development since the 1950s, implying it is an 'emerged' rather than an 'emerging' technology. However, the 'democratisation' of the technology – its widespread and cost-effective public availability – has been a much more recent phenomenon. In this sense, novel applications and their monitoring implications are more associated with an increase in the quantity and quality of the individuals who are monitoring and discussing such imagery. This has led to a rise in the application of the technologies and thus their respective abilities to shape public narratives, especially with regard to nuclear strategy.

OSINT Methodology

Recently, OSINT has evolved into an increasingly popular analytical method, particularly in the field of security studies.[6] However, it is unclear if there is a shared understanding of precisely what OSINT entails and its limitations. OSINT is fundamentally an iterative research methodology that relies on legally collectable, publicly available information. For the purposes of this paper, OSINT is defined as 'intelligence that is produced from publicly available information and is collected, exploited, and disseminated in a timely manner to an appropriate audience for the purpose of addressing a specific intelligence requirement'.[7] Because it is a type of analysis, OSINT does not solely refer to one type of source, but can be thought of as a type of research process, comprising four steps:

1. Identifying a research question.
2. Exploring available data.
3. Analysing data.
4. Evaluating findings.

Recent advances in monitoring technology, particularly relating to publicly available satellite imagery, have helped OSINT add value to traditional intelligence efforts. This is largely because such facilitating technologies can provide more information through expedited and cost-effective means.

Conducting Campaign Analysis

While technology and OSINT are important factors in understanding strategy, campaign analysis provides a distinct methodology for nuclear strategy development. In their research, Rachel Tecott and Andrew Halterman present a formalised method designed to encourage analysts and policymakers to use effective campaign analysis.[8] They describe 'campaign analysis' as:

> a method involving the use of a model and techniques for managing uncertainty to answer questions about military operations. The method involves six steps: 1) formulating a question 2) specifying a scenario 3) constructing a model that represents the military operation 4) setting values for those variables using quantitative research and technical military information 5) running the model with sensitivity analysis and 6) interpreting the output of the model and presenting the conclusions of the analysis.[9]

The provision of OSINT enabled by advanced monitoring technology has enabled campaign analysis to improve in recent years, as more accurate models and values can now be assigned. In considering Tecott and Halterman's definition of campaign analysis, this paper further demonstrates how these three variables (OSINT, monitoring technology and campaign analysis) can shape Chinese nuclear strategy.

OSINT and Chinese Campaign Analysis

Tecott and Halterman's discussion of their campaign analysis method relies on discussions of Wu Riqiang's 2020 model of China's nuclear survivability as exemplary empirical evidence.[10] This section discusses Wu's article and model, placing them alongside Tecott and Halterman's campaign analysis methodology and demonstrating how OSINT, made available through emerging monitoring technology, can improve such analysis.

Wu Riqiang models China's nuclear survivability using campaign analysis and concludes that China's nuclear strategy is founded in uncertain – rather than assured – retaliation.[11] Wu claims China's nuclear growth has been slow and too 'off alert' to meet the minimum deterrence required for an assured retaliation posture.[12] In 1994, China embraced a nuclear philosophy of 'paper tigers', wherein nuclear weapons predominately exist for passive coercion strategies rather than actual use.[13] Implementing this philosophy strategically suggests that China only requires minimal nuclear force for a successful coercive strategy.

Throughout their analysis, Tecott and Halterman emphasise that open sources are already being used in campaign analysis and that OSINT techniques characteristic of emerging monitoring technology (for example, satellite imagery) are becoming increasingly popular.[14] However, OSINT methods are not commonly integrated into *each* step of campaign analysis, particularly in China research. Wu discusses the implications of improved OSINT-enabling technology, such as the effect of satellite imagery on survivability, but only cites one example of the application of such OSINT.[15]

Using Tecott and Halterman's framework, the remainder of this paper demonstrates the strategic implications of integrating more OSINT into Wu's existing Chinese campaign analysis to demonstrate how the two variables, when paired, can yield a more tailored nuclear strategy.

Wu relies on an aggregated two-player nuclear exchange model (developed in the Cold War) and a corresponding probability assessment of Chinese nuclear retaliatory assets survival.[16] Because China has not released a formal nuclear deterrence policy, variables in the specified model are calculated using open source data. Wu is concerned with Chinese nuclear and missile survivability, or the likelihood of a retaliatory Chinese strike, so he limits the model's variables to fixed and mobile nuclear warhead and missile sites. Due to the paucity of verifiable data, Wu argues that the most challenging aspect of his model is 'determining the probability of detection of Chinese nuclear and missiles facilities'.[17] In considering these calculations, Wu points out that fixed sites, or ICBM silos, have higher detection probabilities than mobile launchers and that Chinese adversaries such as the US have used static estimates of the number of DF-5 missiles located at two fixed sites over the years.[18] Conversely, he states that mobile missile sites have a much more variable detection probability due to construction requirements and differing peace and wartime postures.[19]

Despite the relatively early date of its publication, Wu's analysis could have made use of additional OSINT methods to provide more varied assessments in his parameter values, particularly with regard to the detectability probabilities of fixed sites. The discovery of silos in China in June 2021 via satellite imagery could have greatly supplemented Wu's findings. For example, this discovery showed approximately 245 silos under construction at three new sites.[20] If these numbers are correct, it would imply China is taking several measures to expand its fixed-site silos, meaning that keeping estimates of the DF-5 arsenal size and locations constant is less accurate, particularly for future modelled scenarios.

By incorporating sources made available by emerging monitoring technology and OSINT, in future analyses Wu will likely be able to have more confidence in his mobile-site basing structure parameter values (due to increased information and imagery confirmation) and less confidence in fixed-site detectability rates (due to the growing number of fixed-site silos and associated ambiguity regarding the sites' potential use). Ultimately, this suggests that the increase in available OSINT methods, such as satellite imagery, has a very high potential to change Chinese campaign analysis assessments and, potentially, subsequent nuclear strategy.

Conclusions

As China continues to expand and modernise its nuclear deterrent, Wu's campaign analysis suggests states seeking to coerce China into limiting its arsenal should focus on policies restraining the development of strategic capabilities, like missile sites, rather than on warhead limitations alone. Emerging monitoring technology, such as publicly available satellite imagery, paired with OSINT and campaign analysis methodologies, can help facilitate analysis and monitoring of such sites for improved future strategic nuclear success. The satellite imagery discoveries mentioned above demonstrate that China has pivoted towards introducing more uncertainty with regard to its fixed sites. While the sheer number of silo sites rendered them detectable using OSINT, campaign analysis estimates suggest that US strike precision might decline and that China's nuclear survivability might improve. This analysis has shown how OSINT, powered by emerging monitoring technologies, can be integrated into campaign analysis methodologies. By discussing this relationship using a Chinese example, this paper has shown how the three variables can work together to better shape nuclear strategy. Future China nuclear strategy should continue to implement all three variables to ensure strategic success.

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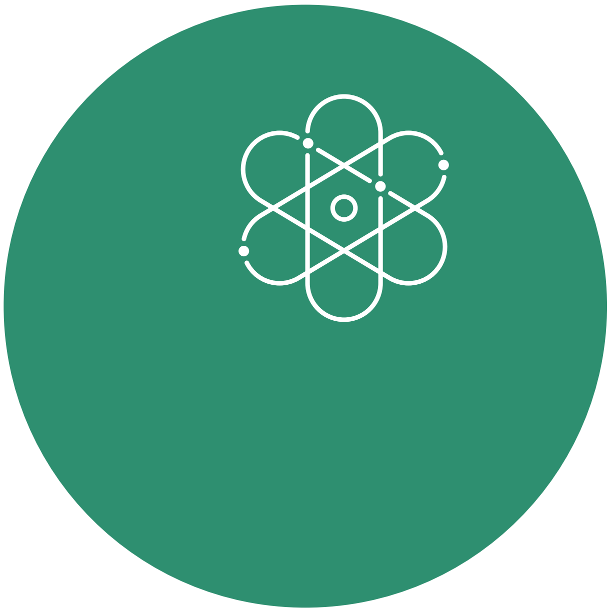

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