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EMERGING VOICES NETWORK

BASIC

Nuclear Harm Reduction

A Policy Cycle by BASIC's Emerging Voices Network (EVN)

Edited by Dave Cullen

Emerging Voices Network

Launched in December 2020, the Emerging Voices Network (EVN) is a digital network of high-potential, next-generation leaders on nuclear issues who will inherit the responsibility to manage nuclear threats. In founding the EVN, BASIC's aim was to create a truly inclusive digital space where younger voices from marginalised communities around the world are heard on nuclear issues. The Network promotes collaboration, dialogue and bridge-building between next-generation leaders from the Global North and South, with diversity and inclusivity at the forefront of the Network's ethos and mission.

BASIC

BASIC is an independent, non-profit think tank working to safeguard humanity and Earth's ecosystem from nuclear risks and interconnected security threats, for generations to come. We have a global reputation for convening distinctive and empathic dialogues that help states overcome complex strategic and political differences. Our established networks and expertise, developed since 1987, enable us to get the right people in the room and facilitate effective, meaningful exchange between siloed and often hostile political communities.

Dave Cullen

Dave is a Policy Fellow at BASIC and Programme Manager of our Emerging Voices Network. He joined BASIC after eight years at the Nuclear Information Service (NIS), where he was the Director. Dave is an expert on the UK nuclear weapons programme, frequently quoted in the press and cited in research. His own publications have covered programmatic and technical problems within the programme, plans for the new UK and US warheads, and the costs of the programme. His work focuses on the interrelationship between technology, policy and politics in relation to weapon systems and disarmament. Prior to working at NIS, he was a researcher for the International Coalition to Ban Uranium Weapons. He is co-chair of the Office for Nuclear Regulation's NGO forum and chair of trustees at the Conflict and Environment Observatory.

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Contents

Introduction

In October 2024 BASIC's Emerging Voices Network (EVN) launched a Policy Cycle examining some of the harms caused by nuclear weapons, and the nuclear industry more broadly. The EVN is a network of early career and young experts from communities, countries, and backgrounds that are under-represented in mainstream nuclear policy fora. Within the overall topic of Reducing Nuclear Harms, EVN members formed five working groups, each focusing on a different type of harm, and proposed ways in which it could be mitigated.

These topics only explore a few harms, rather than a complete overview. Nevertheless, they are as broad and multi-faceted as the ways in which nuclear weapons intersect with, and damage, human lives. As you will see when you read these policy papers, each topic has prompted a different approach from the working group. The recommendations you will find below range from the technological, to the institutional, legal, and philosophical. This is not just a testament to the breadth and depth of the harms caused by nuclear weapons, and the scale of the task of addressing them. It speaks just as much to the talent, persistence and ingenuity of EVN members, and to their refusal to be daunted by that task.

Several themes emerge from the papers. Working groups four and five examined the legacy of nuclear testing, looking respectively at the displacement of people, and harms to service personnel. These papers in particular underscore a lesson seen across all the topics: many harms cannot be undone, or wholly prevented. Some because they are historical, others because they are an intrinsic consequence of the nuclear endeavour. Mitigation is desirable, even necessary, but in moral terms it may not be sufficient.

The long shadow of climate change falls across several of the papers. Working group three considered the climatic consequences of nuclear weapons use, and its implications for doctrines of nuclear deterrence. The studies cited in their paper specifically leverage models originally designed to help us understand anthropogenic climate change.

Working groups one and two looked at opposite ends of the nuclear fuel cycle, considering the long tail of radioactive waste and its extractive front-end: uranium mining. For both of these groups, their topics go beyond nuclear weapons and also encompass nuclear power generation. Despite the steep fall in the costs of renewable power generation, and a corresponding rise in its deployment, an assumption remains in many quarters that an increase in nuclear power generation is required as a mitigation for climate change. These two papers consider some of the ways in which the future harms of a scaled-up nuclear power sector could be reduced.

This study of the complex interplay between nuclear weapons and climate change follows on from previous work by the EVN, particularly our policy cycles on *De-siloing existential threats*. Similarly, this publication is a direct sequel to the 2024 anthology *Strengthening the Humanitarian Impacts of Nuclear Weapons Agenda within the NPT*, including being generously funded by the Norwegian Ministry of Foreign Affairs. At a time when some would prefer to focus on the security perspectives of nuclear-armed states and their allies, both publications remind us that the humanitarian impacts of nuclear weapons have not gone away. These nuclear harms will continue to demand a response, regardless of whether it is politically convenient for nuclear possessor states.

One theme can be found threading through all five papers: justice. It is there in attempts to prevent future generations being saddled with the legacy of our waste, and in calls for the involvement of local communities in decisions about their mineral resources. A constant presence when discussing the global consequences stemming from a limited nuclear exchange, it is most visible in the long struggle for justice of displaced Marshallese people, or when querying the role that compensation schemes might play in legitimising past wrongs. These papers raise some fundamental questions, and challenge us to provide answers that reject the inequities of the past.

This year marks the 80th anniversary of the atomic bombings of Hiroshima and Nagasaki, and the 70th anniversary of the Russell-Einstein manifesto. With seven of the nine nuclear armed states having engaged in military action in the first five months of the year, the world seems very far from the “continual progress in happiness, knowledge, and wisdom” that Russell and Einstein urged us to choose.

The history of the nuclear policy field is so rich and compelling that it would be easy to give in to the temptation to over-focus on the past, or allow historical knowledge to act as a barrier to entry. Instead, we need to look to the future of the field, and harness all the creativity and resources at our disposal, particularly the vitality and sense of moral purpose that is so evident in this anthology. Looking through these papers, I am certain that, if we continue to nurture and support incoming talent, the field has a very bright future. I hope you find them as stimulating and thought-provoking to read as I have found the process of supporting our members to write them.

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June 2025

Solving the Radiological Waste Disposal Riddle

Working Group Members: Shaza Arif (Co-Chair), Abubakar Sadiq Aliyu (Co-Chair), Lucy Wilson, Rohit Kulkarni, Valentine Wangari, Natasha Karner

Introduction

The disposal of radiological waste stands out as a pressing and enduring challenge in the field of nuclear energy. Nuclear power is anticipated to be a major contributor in the global clean energy mix, with the IAEA's high-case scenario forecasting a 2.5-fold increase in nuclear capacity by mid-century compared to current levels,[1] generating stockpiles of radiological waste as an unavoidable by-product. Geological repositories have emerged as a prominent proposed solution in this regard. However, calls for innovative measures in addressing this issue have increased. The paper will focus on three key areas that relate to this issue: Artificial Intelligence (AI) and machine learning (ML), technologies such as Partitioning and Transmutation (P&T) and Small Modular Reactors (SMR).

1 International Atomic Energy Agency (IAEA). New IAEA Report on Climate Change and Nuclear Power Focuses on Financing. October 18, 2024.

Radioactive waste is potentially hazardous and comes from nuclear electricity production, civil and military nuclear applications. According to the IAEA, radioactive waste is classified based on its potential hazard, which determines the type of containment/isolation required.[2] Nuclear waste is typically categorised into three types: low, intermediate, and high. This classification may vary by country but is generally based on the waste's radioactive content and half-life – the time it takes for the waste to lose half of its radioactivity. Low and intermediate level wastes typically result from routine maintenance and operations.[3] Low-level waste (LLW) includes items like contaminated clothing and floor sweepings, while intermediate-level waste (ILW) can include reactor water treatment residues and filters. These make up 97% of the volume of nuclear waste but are less hazardous in comparison to High-level waste (HLW). HLW mainly consists of spent fuel from reactors, which some countries reprocess, producing by-products that also qualify as HLW. It poses a significant radiological risk, requiring long-term isolation, shielding, and cooling due to its high radioactivity and heat generation.[4] The complexity of managing HLW, due to its long-lived radioactivity, necessitates solutions that are capable of isolating the waste from the environment for hundreds or even thousands of years.[5] Several options have been investigated or considered for the long-term disposal of radioactive waste. However, a global consensus supports disposing of radioactive waste in deep geological formations to ensure safe containment. Nature provides examples of stable geological formations that have isolated radionuclides for millions of years.[6] Geological disposal is the emplacement of wastes, without the intention of retrieval, in an appropriate facility at a depth of at least several hundred meters.[7] The following section of the paper analyses radiological waste disposal concerning AI, P&T and SMRs.

AI in Waste Management

Like many other fields, AI and related technologies can find applications in radioactive waste management to enhance processes like classification, treatment, storage, and disposal. For example, machine learning techniques and data analytics tools in the form of pattern recognition, predictive analytics, and fast processing of datasets have been successfully tested for characterising spent fuel assemblies, including burnup, cooling time and initial enrichment, simplifying the process of waste treatment and classification. Using accelerated image processing, AI may also aid in the early detection of potential issues such as leaks, ensuring safe and reliable waste management. There may also be potential to utilise robotic systems and autonomous platforms (supported by AI) to outsource hazardous waste management jobs and reduce human risk exposure.[8] Another application of AI for nuclear waste management is the utilisation of a Digital Twin of the waste management

2 International Atomic Energy Agency, Geological Disposal of Radioactive Waste: Safety Requirements, IAEA Safety Standards Series No. WS-R-4 (Vienna: International Atomic Energy Agency, 2006), https://www-ns.iaea.org/standards/.

3 Jens Birkholzer, Steven J. B. Shaw, Paul Reimus, and William E. Glassley, "Geologic Disposal of High-Level Radioactive Waste: Status, Key Issues, and Trends," Annual Review of Environment and Resources, Lawrence Berkeley National Laboratory, April 12, 2024, https://www.osti.gov/servlets/purl/1210901.

4 Ford, J., and International Atomic Energy Agency, Division of Public Information. Radiation, People and the Environment. Vienna: International Atomic Energy Agency, 2004

5 International Atomic Energy Agency (IAEA). Design Principles and Approaches for Radioactive Waste Repositories. International Atomic Energy Agency, 2020. https://www.iaea.org/publications/13510/design-principles-and-approaches-for-radioactive-waste-repositories.

6 International Atomic Energy Agency. Siting, Design and Construction of a Deep Geological Repository for the Disposal of High-Level and Alpha-Bearing Wastes. Technical Reports Series No. 563. Vienna: International Atomic Energy Agency, 1990. http://www-pub.iaea.org/MTCD/Publications/PDF/te_563_web.pdf.

7 E. B. Ekren et al., Geologic and Hydrologic Considerations for Various Concepts of High-Level Radioactive Waste Disposal in Conterminous United States, Open-File Report 74-158 (Washington, DC: U.S. Geological Survey, 1974).

8 Ibid.

site. This would involve creating a simulation that mirrors the physical site, to do geological modelling, underground construction solutions, and run probabilistic scenarios (including accidents).[9] For example, Deep Geological Repositories (DPR) used for high-level nuclear waste have many engineering and natural complexities. Data-driven machine learning (DDML) could assist physical modelling and provide advantages in calculation efforts and accuracy.[10] Whilst human oversight will still be necessary to assess the outputs of AI and avoid potential errors (such as mischaracterisation of waste products), AI may provide some new opportunities for nuclear waste management.

Partitioning and Transmutation (P&T)

Extreme longevity and radiotoxicity of certain radionuclides remain a pressing challenge. Plutonium, for example, has a half-life of 24,000 years, but remains dangerous for more than 250,000 years.[11] This fundamental challenge thus takes shape: how can society guarantee with any certainty, the containment of dangerous radioactive waste for periods longer than human civilisation has existed?

Given the lack of a guarantee of institutional control and transfer of knowledge over the periods in question, containment breaches are a possibility which have yet to be adequately addressed. This is where Partition and Transmutation (P&T) offers a transformative alternative. By separating (partitioning) the longest-lived radionuclides—namely, minor actinides (MAs) and long-lived fission products (LLFPs)—from spent nuclear fuel and transforming (transmuting) them into shorter-lived or stable isotopes, P&T promises to address the problem of long-term uncertainty in DGR safety.

The hazard period of the longest-lived components of radioactive waste will be shortened by P&T. For example, the necessary isolation period for spent fuel from light water reactors could decrease from over 130,000 to between 500 and 1500 years, with the partitioning and transmutation of waste.[12] Such a reduction in hazard period is significant given the previously stated qualification that, by definition, accidental intrusion can only occur once knowledge of repositories has been lost and institutional regulation of sites has come to an end. A radiotoxicity period of 500-1500 years represents a timescale under which DGRs are predicted to remain under institutional control,[13] during which time accidental intrusion cannot occur.

P&T would also reduce peak dose rates under an intrusion scenario by up to 2 orders of magnitude, representing a significant mitigation of the risk posed to potential future intruders and those exposed to radiation as a result of their activities.[14] While transmutation produces some additional intermediate- and low-level waste through irradiation and contamination of tools and facilities, this is vastly outweighed by reductions in the volume and hazard of high-level waste, as the reduction in peak dose rate represents. P&T does not eliminate the need

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9 Kolditz, Olaf, et al. "Digitalisation for Nuclear Waste Management: Predisposal and Disposal." Environmental Earth Sciences 82, no. 42 (2023). https://doi.org/10.1007/s12665-022-10675-4.

10 Hu, Guang, and Wilfried Pfingsten. "Data-Driven Machine Learning for Disposal of High-Level Nuclear Waste: A Review." Annals of Nuclear Energy 180 (2023). https://doi.org/10.1016/j.anucene.2022.109452.

11 Kristin Shrader-Frechette, Burying Uncertainty: Risk and the Case Against Geological Disposal of Nuclear Waste (Berkeley: University of California Press, 1993), pp. 1. https://publishing.cdlib.org/ucpressebooks/view?docId=ft8s200940&chunk.id=d0e4325&toc.id=&brand=escho.

12 IAEA "Implications of Partitioning and Transmutation in Radioactive Waste Management", Technical Reports Series No. 435, (IAEA, Vienna 2004), p4-7.

13 OECD/NEA, "Deep Geological Repositories and Nuclear Liability"", pp. 43-46.

14 OECD/NEA, "Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation", NEA No. 6894/Nuclear Science, (2011), pp. 53.

for geological repositories. Secondary waste would still have to be stored, albeit for a shorter period and with less stringent containment barriers. However, P&T does enable DGRs to operate within safer, more realistic timeframes. Despite its clear long-term safety benefits, P&T remains at laboratory or pilot scale, and would require further R&D, demonstration and the bridging of infrastructural and regulatory gaps before it can operate on the industrial scale required to unlock benefits to the operation of DGRs. Without targeted policy measures, the risk-reducing advantages of P&T will remain theoretical. To best inform such measures, the main challenges and their corresponding policy implications are outlined below:

Technological Development Challenges: R&D Gaps

Challenge

Key technologies remain underdeveloped, though recent achievements suggest that technological challenges are not inherently insurmountable.

Recommendations

Substantial investment in R&D consortia is needed to develop and test these technologies in real-world conditions. Priority areas include:

- Separation efficiency: the high level of efficiency when separating the longest-lived radionuclides from spent fuel has not yet been achieved for all isotopes, meaning that multiple separation cycles would have to be carried out over hundreds of years for all such components to be extracted from the waste stream. Recent advances (e.g. the addition of yttrium deuteride as a neutron moderator in fast spectrum reactors for the transmutation of LLFPs without the need for partitioning)[15] show potential to carry out partitioning and transmutation simultaneously.
- Fuel fabrication: minor actinide fuels, such as those produced by P&T can pose reactor stability issues; proposed new core designs have been shown to mitigate these issues for certain reactor types,[16] but would require further development and demonstration before they could be upscaled.
- Pyrochemical transmutation methods: these differ from conventional aqueous transmutation methods that rely on water-based acid solutions by using a molten salt or metal bath to dissolve spent fuel. Pyrochemical methods are promising as they generate significantly less secondary waste compared to aqueous methods, which produce radiotoxic solutions, sludges, and spent solvent extraction materials as byproducts. Very little work has been done to demonstrate the effectiveness of pyroprocessing in recent years,[17] necessitating intensified R&D.

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15 Satoshi Chiba, T et al. "Method to Reduce Long-Lived Fission Products by Nuclear Transmutations with Fast Spectrum Reactors." Scientific Reports 7, (2017). https://doi.org/10.1038/s41598-017-14319-7.

16 The new design of a low-void effect core with axial heterogeneities mitigated previously negativ effects of MA loading on the Doppler and void feedback coefficients for Molten Salt Reactors, as shown by Sciora, P., et al. "The Low Void Worth Core Design ('CFV') Based on an Axially Heterogeneous Geometry." Nuclear Engineering and Design 366, 2020: 1-16. https://doi.org/10.1016/j.nucengdes.2020.110763

17 T. Kooyman, "Current state of partitioning and transmutation studies for advanced nuclear fuel cycles", Annals of Nuclear Energy, Volume 157, (2021), 108239. https://doi.org/10.1016/j.anucene.2021.108239.

Technological Integration

Challenge
P&T has not yet been demonstrated as a full "start-to-finish" integrated process.

Recommendations
Shift in focus of R&D work towards the demonstration of P&T technologies as part of an integrated system of waste management and fuel production.

Dependence on Enabling Technologies

Challenge
MAs are more likely to be fissioned into shorter-lived, more stable isotopes in fast spectrum reactors (FSRs)—reactors using fast neutrons as opposed to slow (thermal) neutrons to sustain the fission chain reaction—than they are in thermal reactors. This is because their probability of undergoing fission (fission cross-section) increases significantly with fast neutrons, reducing the likelihood of mere neutron capture and the buildup of heavier, more radiotoxic elements. FSRs are themselves not yet deployed in great numbers at commercial scale,[18] meaning that they are not ready to play a role in a P&T fuel cycle.

Recommendations
Governments should support the deployment of FSRs through direct funding, and regulatory streamlining. Collaboration on shared infrastructure (e.g., test reactors) across nuclear states could accelerate deployment.

Proliferation Risks

Challenge
While not currently an issue, industrial-scale P&T activities/facilities have the potential to pose a significant proliferation risk due to the separation and potential stockpiling of weapons-grade nuclear materials, in particular americium and neptunium, inherent to the process.

Recommendations
Prioritise incorporating proliferation-resistant technologies into P&T, for example by designing reactors and fuel cycles that avoid pure separated streams (e.g., keeping plutonium mixed with minor actinides), integrating partitioning directly with transmutation to prevent material accumulation, and embedding safeguards-friendly features into facility designs.[19]

The logic is clear: Partition and Transmutation is the only available technology that directly reduces the timeframe and severity of the high-impact risks posed by geological repositories. It transforms passive containment into active risk reduction. But without coordinated, sustained policy intervention, the P&T promise will remain unrealised. Governments must therefore treat P&T not as a speculative research area, but as a strategic enabler of nuclear energy's long-term viability, given that P&T, if appropriately supported, offers the only viable path to mitigating long-term uncertainty surrounding deep geological disposal.

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18 "Alternative Reactor Concepts", Federal Office for the Safety of Nuclear Waste Management, [accessed 10 May 2025]. https://www.base.bund.de/en/nuclear-safety/nuclear-technology/alternative-reactor-concepts/alternative-reactor-concepts.html#

19 IAEA, "Implications of Partitioning and Transmutation in Radioactive Waste Management", Technical Reports Series No. 435, (IAEA, Vienna 2004) pp. 27-36.

Small Modular Reactors (SMRs)

SMRs are designed to be smaller, cheaper, and more deployable than conventional reactors, and therefore, built at geographically dispersed locations. This raises urgent questions about not only managing the resulting diverse and geographically dispersed waste streams, but also the logistical challenges in consolidating and transporting SMR waste. These issues are not adequately addressed by legacy waste policies built around large nuclear reactors. SMR waste management could include repurposing existing disposal infrastructure to the specific requirements of SMRs, developing novel waste processing technologies, and creating the necessary frameworks to ensure viable and practical long-term solutions. Below is an overview of SMR waste characteristics by design.

Light Water SMRs

NuScale's VOYGR are similar to pressurised water reactors (PWRs), which primarily use the standard LEU fuel. Their spent fuel needs to be cooled before they can be packed into dry casks and eventually buried deep underground for storage.[20]

High-temperature gas-cooled reactors (HTGRs)

China's HTGRs use an advanced form of nuclear fuel – the Tri-structural Isotropic (TRISO) particle fuel, which is designed to improve the safety and efficiency of the reactor. It consists of tiny uranium particles the size of a poppy seed, wrapped in ceramic layers, and secured in a strong carbon-based coating. It is highly stable and reliable, particularly at high temperatures, however, it creates a greater volume of waste.[21] Germany's Arbeitsgemeinschaft Versuchsreaktor (AVR, a 'pebble-bed reactor' which used similar fuel as the Chinese HTGR had) faced significant delays and cost overruns during its decommissioning in the late 1980s due to the space needed to store its 170,000 fuel pebbles in shielded casks.[22]

Molten Salt Reactors (MSRs)

These can be difficult to manage, as instead of solid fuel rods, MSRs use liquid fuel mixed into molten salts such as fluoride or chloride, depending on the design. When the reactor is shut down, the salts need to be solidified and packaged securely for subsequent disposal. The U.S. Molten Salt Reactor Experiment showed that fluorine gas, which might be released in MSR systems, could complicate safe disposal. Some as-yet-unproven experimental ideas involve turning the MSR waste into glass or ceramic.[23]

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20 Kim, T. K., et al. Waste Management for Three SMR Designs. Argonne National Laboratory, 2022. https://www.anl.gov/article/smr-waste-management.

21 Xerri, C. Management of Spent Fuel from Nuclear Power Reactors. IAEA Bulletin, 2019. https://www.iaea.org/bulletin/smr-waste-management.

22 Theenhaus, R., et al. Storage of AVR and THTR Fuel Elements in CASTOR Casks. Forschungszentrum Jülich, 1994. https://juser.fz-juelich.de/record/281350/files/AVR-THTR-Waste.pdf.

23 Oak Ridge National Laboratory (ORNL). Ending the MSRE – A Cleanup Success Story. 2012. https://www.ornl.gov/news/msre-waste-cleanup.

Sodium-cooled fast Reactors (SFRs)

As identified previously, while fast reactors such as SFRs (e.g., Russia's BREST-300) or the United States' EBR-II are not yet commercially deployed at scale, the pilot demonstration reactors have provided some interesting insights into these technologies. The Russian BREST-300 was shown to generate metallic fuel waste, which can be highly radioactive, and include transuranic isotopes.

Some proposed reactor designs, such as light water SMRS, will produce waste streams that the industry is practised at dealing with, whereas others, such as HTGRs, MSRs and SFRs, pose a more substantial challenge.

Best Practices in SMR Waste Management

- Build It In – SMR designers should consider waste early on, as this problem is best resolved upstream.
- Using what is available – Dry casks and deep underground storage are currently the default approach for most SMRs, and should be the preferred disposal solutions.
- Exploring Waste Minimisation & Reprocessing – Fast reactors and waste reprocessing can reduce waste quantities by extracting more energy from the fuel.
- Secure Interim Storage – Reliable and secure on-site storage provision is essential until permanent repositories become available, which might be decades away in some regions.
- Financial Responsibility – Governments could make SMR operators pay for decommissioning and waste disposal.
- Localised Nuclear Waste Management – Where the nuclear fuel of choice generates waste, it could be reprocessed, managed and disposed of within the country of origin, under the effective supervision of the national government's atomic energy department. This will ensure complete control of the nuclear fuel cycle.

SMRs might differ in how they are built and the waste they generate. Modern systems such as the MSRs and fast reactors create newer forms of waste, the management and disposal of which require further research. Countries with prior experience of managing conventional nuclear waste can integrate SMRs into their nuclear waste management strategy, but those new to SMRs need to build these from scratch. A future without significant long-term multi-generational nuclear waste management issues is challenging, and appropriately regulated SMRs could be one of the ways it could be achieved.

Despite technical progress across several innovative fronts, the global challenge of radiological waste disposal remains deeply unresolved, more due to institutional inertia, economic constraints, and fragmented policy coordination than a lack of viable options. As shown in the preceding sections, solutions like Partitioning and Transmutation (P&T) and AI-assisted waste management offer credible paths to reducing long-lived radionuclides and improving repository efficiency. However, without strategic global investment, standardised safeguards, and an adaptive regulatory environment, these technologies risk stagnation. To move beyond exploratory research and isolated pilot projects, a coordinated international policy effort is needed—one that bridges scientific innovation with implementable, safeguarded, and publicly supported waste strategies. The following recommendations provide a roadmap toward that goal.

Policy Recommendations

The following section of the paper presents these actionable and time-oriented recommendations for meaningful implementation.

1. Establish a global framework for advanced nuclear waste governance led by the IAEA and OECD-NEA, in collaboration with national nuclear regulators, through the creation of a task force.

   - The framework should include timelines for adoption of P&T and SMR as core components of national waste strategies, and focus on standardising practices, regulations and technologies across nations, ensuring all signatories commit to annual reporting on progress of waste minimisation goals.
   - Establish special licensing pathways and transport protocols that account for SMR-specific waste types and volumes.
   - Promote regional/multinational repositories for SMR waste to support countries without national infrastructure.
   - Initiate discussions for an international agreement to allow cross-border processing of nuclear waste, with priority access for countries lacking mature P&T infrastructure.

2. Promotion of strategic investment in Partition & Transmutation (P&T) and adjacent technologies.

   - Launch a global industrialisation fund for P&T and pyroprocessing, co-financed by nuclear states and modelled on IFNEC or ITER structures.
   - Expand R&D funding towards resolving secondary waste issues, a persistent technical hurdle in P&T systems.
   - Promote international financing options, like the World Bank green funds, for ADS and fast reactor development, given the lower, long-term waste and climate impact they present.
   - Encourage national policy tools such as tax incentives, waste reduction mandates and policy integration of P&T to improve operator buy-in.
   - Explicitly promote pyroprocessing as a strategic enabler for safer, proliferation-resistant closed fuel cycles.

3. Integration of AI and Robotics for long-term waste management and monitoring.

   - Launch pilot AI projects to model behaviour of radioactive waste in deep geological repositories (DGRs).
   - Fund robotics R&D for handling high-radiotoxic spent fuel and SMR-specific waste streams.
   - Develop a global roadmap for standardising AI-driven monitoring in nuclear waste infrastructure over the next two decades.

4. Reinforcement of non-proliferation and safeguards for emerging fuel cycles.

   - Initiate early integration of P&T technologies into IAEA safeguards, including safe certification for pyroprocessing and advanced reactors.
   - Expand non-proliferation frameworks to cover new isotopes and materials, like Uranium-233, which pose monitoring challenges due to low detectability and latent weaponisation potential.
   - Work towards amendment of the Nuclear Suppliers Group guidelines to reflect the proliferation risks posed by emerging fuel cycles.
   - Develop monitoring protocols across the full lifecycle of sensitive materials involved in P&T, including separation, transport and storage.

5. Strengthening economic justification through holistic cost-benefit analysis.

   - Support the development of clear cost-benefit models for P&T and advanced reactor systems to build investor confidence.
   - Employ Analytic Hierarchy Process (AHP) to compare open and closed fuel cycle schemes, which enables integration of long-term human and environmental security outcomes alongside traditional economic indicators.
   - Generate emphasis on previously under-considered value of reduced long-term intrusions and radiotoxicity risk as a central benefit of P&T-enabled fuel cycles.

6. Advancement of diplomacy and public engagement for long-term legitimacy.

   - Integrate advanced fuel cycle policy and nuclear waste safeguards into non-proliferation diplomacy.
   - Expand nuclear mandates to cover novel proliferation risks from advanced waste processing.
   - Development of a supplementary protocol under the Espoo Convention in a transboundary context for SMR-specific environmental and humanitarian guidance, and/or a model clause under IAEA or NEA frameworks to bind future SMR deployments to post-facto review if novel impacts are detected.
   - Ensure the community consultation and Human Health Risk Assessments (HHRA) are standardised around SMR siting and repository development.
   - Present P&T publicly as a tool for the reduction of radiotoxicity and dose rate, strengthening both safety and stakeholder legitimacy.
   - Launch international forums on AI in nuclear waste solutions, and engage the private sector actors and technical communities.

Conclusion

The study has explored the radiological waste disposal challenges through a technological lens, focusing on three major components. The study shows that sustainable management of radiological material must be ensured for the optimal usage of nuclear energy. The study demonstrates that AI and related technologies could be utilised to address issues regarding advanced algorithms, digital twins, and outsourcing dangerous tasks concerning radiological waste disposal. Similarly, P&T technology has the potential to offer solutions for radiological waste disposal. The decentralised nature of SMR requires new frameworks that are tailored to meet the contemporary requirements vis-à-vis existing repositories. This involves management techniques, taking into account the design, size, and operation of Small Modular Reactors (SMRs).

However, numerous economic and regulatory challenges stand in the way of the seamless employment of these technologies. To address the imminent challenges ahead, the paper proposes several recommendations. The overall theme of these recommendations includes transforming radiological waste from a long-term liability to a more manageable form in the future. These include investing financial resources in advanced research and development (R&D), coordinating diplomatic efforts, establishing necessary agreements, forming new policies related to SMRs, and enhancing infrastructure development and resilience.

While the challenges related to radiological waste disposal are significant, they are not insurmountable. Through the use of emerging technologies, international cooperation, robust regulations, and prioritising environmental security, the global community can create a sustainable environment for radiological waste disposal. Such efforts are likely to ensure safe use of nuclear energy while contributing to a sustainable future.

Offsetting Harms Relating to the Front End of the Nuclear Fuel Cycle

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Introduction

The current era is witnessing a renewed interest in exploring low-carbon and alternative energy sources owing to growing energy demand and concerns regarding the climate crisis. At an International Symposium on Uranium Raw Material for the Nuclear Cycle (URAM-2023), IAEA Director General Rafael Mariano Grossi emphasized that meeting UN Sustainable Development Goals (SDGs) and achieving the Paris Agreement targets hinges on adapting to the right sources of energy.[1] In this regard, most of the Intergovernmental Panel on Climate Change's (IPCC) models that limit global warming to 1.5°C by 2050 include an increase in nuclear power.[2] Likewise, a

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1 Jeffer Donovan, "IAEA Symposium Examines Uranium Production Cycle for Sustainable Nuclear Power," IAEA, May 12, 2023, https://www.iaea.org/newscenter/news/iaea-symposium-examines-uranium-production-cycle-for-sustainable-nuclear-power.

2 Intergovernmental Panel on Climate Change (IPCC), Global Warming of 1.5°C report (Geneva: IPCC, 2018), https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.

report by McKinsey argues that scaling economies would require acceleration of nuclear energy sources.[3] As nuclear energy requires uranium, this could trigger a modern-day 'uranium rush,' reminiscent of the 1950s when stakeholders scrambled to secure uranium.[4]

As of 2022, about 60,000 tons of uranium are required to fuel the world's 410 operating nuclear power reactors annually.[5] The demand for uranium could reach up to 100,000 per year by 2040, an increase of 66 percent.[6] At present, the world's largest-producing uranium mines are located in Canada, Namibia, Kazakhstan, Australia, and Nigeria.[7] In 2022, Kazakhstan produced 43% of the world supply, followed by Canada, which produced 15%, and Namibia at 11%.[8]

This policy paper aims to conduct a comprehensive assessment of the adverse effects related to uranium mining, part of the front end of the nuclear fuel cycle, which is an often-overlooked aspect of nuclear energy. The front end of the nuclear fuel cycle encompasses the processes involved in preparing uranium for use in nuclear reactors and weapons, including mining, milling, refining, conversion to uranium hexafluoride (UF_6), enrichment, and fuel fabrication. By analysing scientific studies, regulatory frameworks, and case studies, this paper provides a synopsis of harms related to uranium mining while offering eight recommendations to address them.

Harms Related to Uranium Mining

The paper focuses on four key harms related to uranium mining and their mitigation strategies:

1. Health and Environmental Harms
2. Land Rights and Revenue
3. IAEA Safeguards and Proliferation Harms/Risks
4. The Geopolitics of Uranium Mining

Health and Environmental Harms

Uranium mining presents grave risks to human health, primarily through both radiological and non-radiological exposures. Radiological exposure, particularly to uranium-238, radon gas, and radioactive dust, significantly elevates the risk of lung cancer, leukaemia, and other respiratory illnesses among miners and nearby

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3 Mekala Krishnan, Chris Bradley, Humayun Tai, Tiago Devesa, Sven Smit, and Daniel Pacthod, The Hard Stuff: Navigating the Physical Realities of the Energy Transition, report (New York: McKinsey & Company, August 2024), https://www.mckinsey.com/~/media/mckinsey%20global%20institute/our%20research/the%20hard%20stuff%20navigating%20the%20physical%20realities%20of%20the%20energy%20transition/the-hard-stuff-navigating-the-physical-realities-of-the-energy-transition-final.pdf.

4 Nate Housley, "The Uranium Boom and Free Enterprise | Utah Division of State History," history.utah.gov, n.d., https://history.utah.gov/the-uranium-boom-and-free-enterprise/.

5 Nuclear Energy Agency and International Atomic Energy Agency, "Uranium 2022 Resources, Production and Demand" (Paris: OECD, 2023), https://www.oecd-nea.org/jcms/pl_79960/uranium-2022-resources-production-and-demand.

6 Idem

7 World Nuclear Association, "Uranium Mining Overview – World Nuclear Association," world-nuclear.org, May 16, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.

8 World Nuclear Association, "World Uranium Mining Production – World Nuclear Association," World Nuclear Association, April 30, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.

communities.[9] Prolonged inhalation of radon and ingestion of radioactive particulates lead to bioaccumulation of toxic substances within the human body.[10] Non-radiological exposure to heavy metals such as arsenic and cadmium, commonly found alongside uranium deposits, further exacerbates health risks by causing kidney damage, neurological impairments, and cardiovascular conditions.[11] The dangers are not limited to chemical exposure: physically extreme working conditions—including prolonged underground shifts, poor ventilation, elevated temperatures, and inadequate hydration—contribute to heat stress, dehydration, and cardiovascular strain. In many regions, particularly parts of Africa and among Indigenous populations, uranium mining has historically been marked by exploitative labour practices, limited safety standards, and inadequate healthcare access.[12]

The environmental consequences of uranium mining are severe, multifaceted, and long-lasting. Open-pit mining operations cause extensive soil degradation and the destruction of surrounding ecosystems, while underground mining and tailings storage release radioactive dust and toxic runoff into the environment.[13] Tailings, often containing heavy metals and radioactive materials, can leach into nearby rivers, aquifers, and agricultural lands if not properly managed. In situ leaching (ISL) methods, employed extensively in countries like Kazakhstan, involve injecting chemical solutions underground to dissolve uranium deposits; however, these solutions frequently migrate beyond intended boundaries, contaminating groundwater systems crucial for local populations.[14] Poorly managed tailings dams, especially in low-income or conflict-affected regions, pose catastrophic risks, with structural failures resulting in long-term ecological damage.[15] The Navajo Nation in the United States offers a stark example: decades after mine closures, radioactive contamination has led to elevated cancer rates, reproductive disorders, and widespread psychological distress among affected communities.[16] Furthermore,

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9 Paul A. Locke et al., Uranium Mining in Virginia: Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in Virginia (Washington, D.C.: National Academies Press, 2012), https://doi.org/10.17226/13266.

10 Ibid

11 Ibid

12 Nuclear Free, "Africa: Supplier for the Wealthy North," nuclear-free.com, accessed March 27, 2025, https://www.nuclear-free.com/uranium-article/articles/africa-supplier-for-the-wealthy-north.html.;
Alice Segal, "Uranium Mining and the Navajo Nation—Legal Injustice," Southern California Review of Law and Social Justice 21 (2012), https://gould.usc.edu/students/journals/rlsj/issues/assets/docs/volume21/Spring2012/2.Segal.pdf

13 Steve Russell, "Unearthing the Environmental Consequences of Uranium Mining," Environment Co (Environment.co, November 28, 2023), https://environment.co/unearthing-the-environmental-consequences-of-uranium-mining/.
Zehui Zhang et al., "Study on the Ecotoxic Effects of Uranium and Heavy Metal Elements in Soils of a Uranium Mining Area in Northern Guangdong," Toxics 11, no. 2 (January 20, 2023): 97–97, https://doi.org/10.3390/toxics11020097.
Ariel Gould, "Sustainable and Ethical Uranium Mining: Opportunities and Challenges | Good Energy Collective," www.goodenergycollective.org, August 31, 2022, https://www.goodenergycollective.org/policy/sustainable-and-ethical-uranium-mining-opportunities-and-challenges.

14 Thomas Borch, Nicholas Roche, and Thomas E. Johnson, "Determination of Contaminant Levels and Remediation Efficacy in Groundwater at a Former in Situ Recovery Uranium Mine," Journal of Environmental Monitoring 14, no. 7 (2012): 1814, https://doi.org/10.1039/c2em30077j.
Locke, Uranium Mining in Virginia. (National Academies Press, 2012).

15 World Nuclear Association. "Occupational Safety in Uranium Mining." Updated August 27, 2024. https://world-nuclear.org/information-library/safety-and-security/radiation-and-health/occupational-safety-in-uranium-mining.aspx.

16 Dewar, Dale, Linda Harvey, and Cathy Vakil. "Uranium Mining and Health." Canadian Family Physician 59, no. 5 (2013): 469-471;Locke et al., Uranium Mining in Virginia;Segal, Alice. "Uranium Mining and the Navajo Nation—Legal Injustice." Review of Law and Social Justice 21, no. 3 (2012): 355-380.

the long-lived nature of radioactive decay demands sustained containment and oversight.[17] Climate change compounds these environmental risks by increasing the mobility of contaminated dust, intensifying rainfall events that strain tailings dams, and heightening the likelihood of infrastructure collapse.[18] Without robust and adaptive management strategies, the environmental legacy of uranium mining can persist for millennia.

Addressing the health and environmental harms of uranium mining demands a multi-layered and inclusive approach. First, mining operations must be governed by sustainable resource management frameworks aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 16 (Peace, Justice, and Strong Institutions). Governments must strengthen occupational safety regulations, mandating the provision of protective equipment, improved underground ventilation systems, continuous health monitoring, and adopt safer extraction techniques to minimise exposure to radioactive materials. Mining companies must be held accountable for worker health outcomes, especially in regions where labour protections are historically weak. Simultaneously, environmental governance should require the establishment of mine closure and rehabilitation strategies from the outset of each project, supported by financial guarantees to ensure that remediation efforts are not abandoned.[19] International cooperation initiatives, such as the IAEA and EBRD-supported remediation projects in Kyrgyzstan, demonstrate the critical role of cross-border support in addressing underfunded legacy sites.[20] Similarly, the application of advanced technologies such as reverse osmosis and ion exchange for water treatment, as implemented in Canada's uranium sector, highlights the possibilities for mitigating contamination.[21] Crucially, Indigenous and local populations must be actively involved in all stages of mining operations—from planning to closure—to ensure that their rights, health, and livelihoods are protected. Integrating robust environmental oversight with strong public health protections and inclusive governance models offers the only path toward making uranium mining safer and more socially accountable.

Land Rights and Revenue

A significant harm stemming from the front end of the nuclear fuel cycle is the mismanagement of rights and revenue generated from uranium mining. The relationship between governments, mining companies, and local communities is frequently characterised by power imbalances, with contracts often negotiated behind closed

17 Keyanna, Teracita, Rebecca Neal, and Carmela Roybal. "The Health Impacts of Uranium Mining in Native American Communities: Policy Brief." Native American Budget and Policy Institute, 2024.

18 Gesai, Sheil. "Mining Indigenous Communities: A Long Legacy." Kleinman Center for Energy Policy, December 20, 2021. https://kleinmanenergy.upenn.edu/commentary/blog/mining-indigenous-communities-a-long-legacy/.

19 European Commission, "Environmental Rehabilitation and Repurposing Toolkit," European Commission, 2023, https://energy.ec.europa.eu/topics/oil-gas-and-coal/eu-coal-regions/knowledge-products-draft/environmental-rehabilitation-and-repurposing-toolkit_en.

20 Camilla Aznabakiyeva, "Canada Sets Goal to Outperform Kazakhstan as Major Global Uranium Producer within Five Years," Kursiv Media Kazakhstan, January 6, 2025, https://kz.kursiv.media/en/2025-01-06/engk-tank-canada-sets-a-goal-to-outperform-kazakhstan-as-major-global-uranium-producer-within-five-years/; World Nuclear Association, "Uranium in Tajikistan – World Nuclear Association," World Nuclear Association, February 21, 2022, https://world-nuclear.org/information-library/country-profiles/countries-t-z/tajikistan#legacy-waste-from-uranium-mining.

21 IAEA, "Best Practice in Environmental Management of Uranium Mining" (Vienna: IAEA Nuclear Energy Series, 2010), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1406_web.pdf.

doors.[22] As a result, communities are marginalised, losing access to their land and receiving limited economic benefit, which fosters mistrust and deepens inequality.

To address these challenges, this paper suggests a Common-Pool Resources (CPR) framework, which enables a more equitable governance structure.[23] Under this model, the government acts as a neutral mediator, safeguarding community rights, facilitating fair revenue-sharing, and supporting conflict resolution.[24] The government must ensure that the provisions for indigenous benefit-sharing are explicitly included in mining contracts, particularly during phases of high profitability.[25] Governments should also require companies to invest in local infrastructure during the early stages of site development. The CPR framework is unlikely to be effective where state control on assets is not transparent or where institutional arrangements governing the use of resources are weak.[26] However, it is applicable in resource-rich regions with strong customary land rights where splitting of resources is difficult.[27]

Mining companies must take responsibility not only for employment but also for ensuring local participation in decision-making.[28] This includes appointing community members to advisory roles and reserving opportunities for women-led enterprises. Support should also extend to vocational training, healthcare services, and education. Such integration fosters co-ownership and reduces the likelihood of operational delays.[29]

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22 OECD Nuclear Energy Agency (NEA), Maximising Uranium Mining's Social and Economic Benefits: A Guide for Stakeholders, report (Paris: Organisation for Economic Co-operation and Development, 2022) https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/09/maximising-uranium-mining-s-social-and-economic-benefits_7a0a5e78/a2b420bf-en.pdf; Howard Mann, IISD Handbook on Mining Contract Negotiations for Developing Countries, International Institute for Sustainable Development (IISD), April 2015, https://www.iisd.org/system/files/publications/iisd-handbook-mining-contract-negotiations-for-developing-countries-volume-1.pdf.

23 J.C Lovett, C.H. Quinn, D.G. Ockwell and R. Gregorowski, Common Pool Resources, report (York: Centre for Ecology, Law and Policy, University of York, UK, 2005), https://assets.publishing.service.gov.uk/media/57a08c6ced915d3cfd0013a6/R8501AnnB5.pdf; Elinor Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, 1990.

24 J.C Lovett, C.H. Quinn, D.G. Ockwell and R. Gregorowski, Common Pool Resources;
Tony Andrews, Jonathan Gamu, Philippe Le Billon, Chang Hoon Oh, David Reyes and Jioung Shin, The Role of Host Governments in Enabling or Preventing Conflict Associated With Mining, report (Vancouver: UNDP)

25 Uyanga Gankhuyag and Fabrice Gregoire, "Managing Mining for Sustainable Development" (Bangkok: UNDP, April 2018), https://www.undp.org/sites/g/files/zskgke326/files/publications/UNDP-MMFSD-HighResolution.pdf

26 Peter Ward, Andrei Lankov and Jiyoung Kim, "Common-Pool Resource Depletion and Dictatorship: North Korean Coastal Fishing in the Age of Marketization," Communist and Post-Communist Studies 55, no 1, March 2022, https://online.ucpress.edu/cpcs/article/55/1/183/120317/Common-Pool-Resource-Depletion-and.

27 J.C Lovett, C.H. Quinn, D.G. Ockwell and R. Gregorowski, Common Pool Resources, report (York: Centre for Ecology, Law and Policy, University of York, UK, 2005), https://assets.publishing.service.gov.uk/media/57a08c6ced915d3cfd0013a6/R8501AnnB5.pdf.

28 Gregory Poelzer, "Corporate Engagement Strategies in Northern Mining: Boliden, Sweden and Cameco, Canada," Environ Manage July 27, no 4 (2023): 838-849, https://pmc.ncbi.nlm.nih.gov/articles/PMC10460324/.

29 OECD Nuclear Energy Agency (NEA), Maximising Uranium Mining's Social and Economic Benefits: A Guide for Stakeholders, report (Paris: Organisation for Economic Co-operation and Development, 2022) https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/09/maximising-uranium-mining-s-social-and-economic-benefits_7a0a5e78/a2b420bf-en.pdf; Timothy O. Williams, "Multiple Uses Of Common Pool Resources In Semi- Arid West Africa: A Survey Of Existing Practices And Options For Sustainable Resource Management," Natural Resource Perspective 1998, no 38, https://media.odi.org/documents/2885.pdf.

Case comparison demonstrates the effectiveness of inclusive governance models, such as co-managed mines in Saskatchewan in Canada, compared to mismanaged examples like the Ranger Uranium Mine in Australia.[30] The IAEA can play a key role by disseminating best practices and helping to formalise these responsibilities globally, in addition to expanding oversight over the nuclear fuel cycle.[31]

IAEA Safeguards and Proliferation Harms/Risks

Existing safeguards primarily focus on the enrichment and reprocessing stages, offering limited oversight of uranium mining and milling, the earliest and most opaque phases of the nuclear fuel cycle.[32] Although proliferation risks at this stage are relatively low, the front end remains vulnerable to state diversion and unauthorized access by non-state actors.[33] In regions with weak governance or ongoing conflict, the risk of illicit extraction, theft, or trafficking of uranium ore or concentrates is significantly heightened.[34] Past incidents involving sabotage and the black-market trade of nuclear materials have highlighted the need for tighter controls at these early stages.[35]

While the Model Additional Protocol (AP) permits inspections at mining sites, its implementation is uneven and lacks uniform enforcement.[36] Many countries either have not ratified the protocol or apply its provisions selectively, creating oversight gaps that could allow undeclared uranium stockpiling or diversion to go undetected.[37] To address these shortcomings, rather than expanding the AP to include materials with minimal direct proliferation risks, efforts should focus on strengthening the transparency and reporting obligations related to uranium extraction and movement. This must be supported by the development of real-time tracking systems, satellite imagery, and artificial intelligence to identify anomalies and ensure early intervention.[38]

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30 Geordan Graetz, "Ranger Uranium Mine and the Mirarr (Part 1), 1970–2000: The Risks of 'Riding Roughshod,'" The Extractive Industries and Society 2, no. 1 (January 2015): 132–41, https://doi.org/10.1016/j.exis.2014.10.004;Simon Johanson, "Rio Tinto to Take Full Control of Controversial Mine in Kakadu," The Sydney Morning Herald, November 20, 2024, https://www.smh.com.au/business/companies/rio-tinto-moves-to-shut-down-controversial-mine-in-kakadu-20241120-p5ks2q.html.

31 International Atomic Energy Agency (IAEA), "Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development," IAEA Nuclear Energy Series No. NF-T-1.1.(Vienna: International Atomic Energy Agency, 2009) https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1401_web.pdf; International Atomic Energy Agency (IAEA), "Best Practice in Environmental Management of Uranium Mining" IAEA Nuclear Energy Series No. NF-T-1.2. (Vienna: International Atomic Energy Agency, 2010), https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1406_web.pdf.

32 Y. Kuno, N. Inoue, and M. Senzaki, "Nuclear Proliferation-Resistance and Safeguards for Future Nuclear Fuel Cycle," Journal of Nuclear Materials 385, no. 1 (2009): 153–56.

33 Stephen Herzog, "The Nuclear Fuel Cycle and the Proliferation 'Danger Zone,'" Journal for Peace and Nuclear Disarmament 3, no. 1 (January 2, 2020): 60–86, https://doi.org/10.1080/25751654.2020.1766164.

34 Hastings, Justin V., and Cindy Vestergaard. "Safeguards and security risks at the (very) front end of the nuclear fuel cycle." The Nonproliferation Review 25, no. 5-6 (2018): 457-476.

35 Andy Oppenheimer, "The Nuclear Black Market: Extent and Countermeasures." Royal United Services Institute, November 1, 2005. https://www.rusi.org/publication/nuclear-black-market-extent-and-countermeasures.

36 Y. Kuno, N. Inoue, and M. Senzaki, "Nuclear Proliferation-Resistance and Safeguards for Future Nuclear Fuel Cycle," Journal of Nuclear Materials 385, no. 1 (2009): 153–56.

37 International Atomic Energy Agency, Nuclear Security in the Uranium Extraction Industry, IAEA-TDL-003 (Vienna: IAEA, 2016).

38 International Atomic Energy Agency, "Additional Protocol," IAEA, accessed March 23, 2025, https://www.iaea.org/topics/additional-protocol.

These efforts should also reflect obligations under UNSCR 1540[39] and the Convention on Physical Protection of Nuclear Material (CPPNM) and Amendment,[40] both of which support measures to prevent non-state actors' access and ensure physical security during international transport of nuclear materials.

In parallel, the IAEA's authority should be strengthened through bilateral and multilateral agreements, such as information sharing protocols and standardized reporting that reinforce transparency across the supply chain. While the CPPNM[41] and Nuclear Suppliers Group (NSG)[42] guidelines address transport and export controls enforcement, gaps persist. The IAEA can continue to support implementation by coordinating compliance efforts, providing technical assistance, and promoting harmonised practices. Closer cooperation beyond current bilateral arrangements between national regulators and international non-proliferation bodies is essential to ensure consistent monitoring of uranium flows and trading practices, particularly in high-risk environments and geopolitical tensions.

Geopolitics of Uranium Mining

Uranium's strategic role in both energy and defense makes its extraction and control highly susceptible to geopolitical tensions. Supply chains can be disrupted by conflict, sanctions, or political leverage, placing energy security and nuclear stability at risk.

Russia's dominant position in the global nuclear fuel supply chain, creates a structural dependency for several European states.[43] Countries such as Hungary, Slovakia, and the Czech Republic, which were previously part of the Cold War communist bloc, rely heavily on Russia-supplied nuclear fuel for their energy grids, due to long-term contracts and reactor designs compatible only with Russian fuel assemblies.[44] This reliance reduces their strategic autonomy, making it more difficult to align with broader EU foreign policy objectives or impose sanctions without risking energy insecurity.[45] It also exposes these states to abrupt supply disruptions during geopolitical crises, as seen in the aftermath of Russia's invasion of Ukraine.[46] Such dependency is not only a

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39 United Nations Office for Disarmament Affairs, Security Council Resolution 1540 (2004), https://disarmament.unoda.org/wmd/sc1540/#:~:text=In%20resolution%201540%20%282004%29%2C%20the%20Security%20Council%20decided,means%20of%20delivery%2C%20in%20particular%20for%20terrorist%20purposes.

40 International Atomic Energy Agency, Convention on the Physical Protection of Nuclear Material and Its Amendment, https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment#:~:text=The%20CPPNM%20establishes%20legal%20obligations%20for%20Parties%20regarding,taking%20of%20nuclear%20material%20or%20credible%20threat%20thereof.

41 International Atomic Energy Agency, Convention on the Physical Protection of Nuclear Material and Its Amendment, https://www.iaea.org/publications/documents/conventions/convention-physical-protection-nuclear-material-and-its-amendment.

42 Nuclear Suppliers Group, NSG Guidelines, https://nuclearsuppliersgroup.org/index.php/en/guidelines/nsg-guidelines.

43 Gilbert, Alex, and Morgan Bazilian. "Russia's Energy Clout Doesn't Just Come from Oil and Gas – It's Also a Key Nuclear Supplier." The Conversation, March 18, 2022. https://theconversation.com/russias-energy-clout-doesnt-just-come-from-oil-and-gas-its-also-a-key-nuclear-supplier-179444.

44 Ioannis E. Kotoulas and Wolfgang Pusztal, "Geopolitics of the War in Ukraine " (Athens: Foreign Affairs Institute, June 2022), https://www.aies.at/download/2022/Geopolitics-of-the-War-in-Ukraine-FINAL.pdf.

45 European External Action Service. "Energy Policy Is at the Centre of EU Foreign Policy." Accessed April 3, 2025. https://www.eeas.europa.eu/eeas/energy-policy-centre-eu-foreign-policy_en.

46 Modern Diplomacy, "The Invasion of Ukraine and Its Impact on European Energy Security," August 15, 2024, https://moderndiplomacy.eu/2024/08/15/the-invasion-of-ukraine-and-its-impact-on-european-energy-security/.

technical vulnerability but also a geopolitical lever, which can be exploited to exert pressure or shape diplomatic alignments in times of conflict or tension.

The war against Ukraine illustrates these risks.[47] Conflict in uranium-rich areas like Kirovohrad Oblast has severely disrupted production and infrastructure, exemplified by the decline in output from VostGOK,[48] which previously produced up to 830 tons of uranium per year, and only produced 120 tons in 2022.[49] Such instability also raises concerns about the targeting or militarisation of uranium sites, exacerbating fears of proliferation and environmental disaster.[50]

To mitigate these risks, countries must diversify their sources of uranium, reduce reliance on dominant suppliers, and build domestic resilience. Regional cooperation (e.g., through Euratom or Urenco) must be complemented by national-level investment in extraction capacity and infrastructure.[51] In addition to these measures, strategic uranium reserves, modelled on oil stockpiles, could buffer against future supply disruptions.[52] At the international level, mechanisms like the IAEA's Low Enriched Uranium Bank in Kazakhstan provide a vital backup supply of nuclear fuel for eligible countries, helping to reduce geopolitical vulnerabilities and support non-proliferation goals.[53]

Global stability also depends on preventing environmental contamination and radiological threats during armed conflict. This requires new bilateral and multilateral protocols to protect uranium infrastructure and ensure continuity of oversight even in wartime conditions.

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47 Nataliya Struk, "1 the Effect of the War on Ukrainian Economy," in The Economics of Russia's War in Ukraine: Impact Analysis of Economic Policy and Finance (New York: Routledge, 2024).

48 Vostochny Gorno-Obogatitelny Kombinat (Eastern Mining and Processing Plant), is a state-owned Ukrainian enterprise specializing in uranium mining and processing.

49 World Nuclear Association, "Ukraine," World Nuclear Association, https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine#:~:text=Pilot%20production%20at%20Novokonstantinovskoye%20took%20place%20in,Vody%2C%20close%20to%20the%20border%20of%20Kirovograd.

50 Teva Meyer, "Assessing the Weaponability of Enriched Uranium Trade in the Geopolitics of Nuclear Energy: The EU-Russia Interrelations," Resources Policy 86 (October 1, 2023): 104318, https://doi.org/10.1016/j.resourpol.2023.104318.

51 Gloria Rodríguez-Pina and Ignacio Fariza, "EU Launches Plan to Secure Supplies of 17 Strategic Raw Materials," El País, March 25, 2025, https://english.elpais.com/international/2025-03-25/eu-launches-plan-to-secure-supplies-of-17-strategic-raw-materials.html.

52 Oxford Analytica, "Ukraine War Alters Mineral Market Dynamics," Oxan.com, February 24, 2023, https://dailybrief.oxan.com/Analysis/DB276279/Ukraine-war-alters-mineral-market-dynamics.

53 IAEA, "IAEA Low Enriched Uranium (LEU) Bank", accessed May 2025, https://www.iaea.org/topics/iaea-low-enriched-uranium-bank

Recommendations:

1. Extend transparency measures to the under-regulated stages of the Nuclear fuel cycle

   - The IAEA's Additional Protocol currently focuses on enrichment and reprocessing, offering limited oversight of uranium mining and milling.
   - *Recommendation:* Rather than extending safeguards, the IAEA and member states should strengthen transparency and reporting requirements at the front end of the fuel cycle. This could include implementing real-time tracking systems, satellite surveillance, and AI-driven anomaly detection to ensure early identification of risks and full-cycle accountability.
   - *Desired Outcome:* Improved early-stage transparency and consistency in uranium tracking, reducing the risk of illicit accumulation and reinforcing international confidence without expanding full scope safeguards into stages with minimal direct proliferation risk.

2. Establish a global convention on environmental and safety standards in uranium mining

   - There is no binding international framework that ensures consistent environmental, labour, and safety standards in uranium extraction.
   - *Recommendation:* Create a global treaty, such as the Minamata Convention on Mercury or the UN Convention on the Law of the Sea, that sets enforceable standards for environmental protection, labour rights, and mine rehabilitation. Incorporate IAEA-like protocols as the baseline for global compliance.
   - *Desired Outcome:* Greater global regulatory consistency and reduced exploitation of weak jurisdictions by mining firms.

3. Strengthen and expand IAEA oversight across the uranium supply chain

   - Fragmented international monitoring allows harmful practices in politically fragile and resource-rich regions.
   - *Recommendation:* Extend IAEA oversight beyond safeguards to include technical cooperation tools for environmental monitoring, such as radiation mapping, heavy metal contamination, and water safety testing, while integrating the expertise and mandate of other relevant UN bodies, particularly the United Nations Environmental Programme (UNEP). Countries should be required to report extraction volumes, document environmental conditions at mining sites, and implement secure protocols for uranium facilities in or near conflict zones. This expansion should be formalised through a joint UNEP-IAEA working group or mandated via the IAEA's Technical Cooperation Programme.
   - *Desired Outcome:* Improved global governance, enhanced transparency, and reduced risk of "blood uranium" exploitation in conflict-affected zones.

4. Institutionalise domestic safety standards and community health protocols

   - Uranium mining continues to harm workers and surrounding communities due to inadequate domestic regulation.
   - *Recommendation:* Mandate the adoption of comprehensive occupational safety measures, environmental sensors in affected communities, and binding Health and Environmental Impact Assessments (H/EIAs) with local approval powers—especially on Indigenous land. National governments should be required, potentially as a condition of IAEA technical assistance, to adopt these protocols domestically.
   - *Desired Outcome:* Lower health risks, stronger local protection, and more democratic oversight of mining operations.

5. Align trade policy with environmental and human rights compliance

    - Weak global enforcement allows unsafe uranium to flow across borders despite social and ecological harm.
    - *Recommendation:* Uranium-importing states, especially those in the EU or OECD, should impose conditionality on imports, tying purchases to compliance with IAEA-equivalent safety standards. Require liability bonds from firms to cover future environmental remediation.
    - *Desired Outcome:* Trade becomes a lever for accountability, incentivising socially responsible uranium production and reducing long-term environmental damage.

6. Create economic resilience mechanisms for mining regions

    - Regions dependent on uranium mining may face economic vulnerability and social unrest as resource cycles shift.
    - *Recommendation:* Allocate a portion of mining profits into IAEA-supervised, locally governed diversification funds that invest in renewable energy, vocational training, and local infrastructure. Use a flexible contribution model based on the mine's life cycle.
    - *Desired Outcome:* Diversified, more resilient local economies and a reduction in dependency on uranium as a primary revenue source.

7. Mandate mine closure trust funds and global contract transparency

    - Mine closures often leave environmental damage and broken promises to local populations due to opaque contracts and underfunded remediation.
    - *Recommendation:* Require mining companies to deposit closure and rehabilitation funds into independent trust mechanisms, managed by national regulators or supervised by entities like the IAEA or UNEP, with host government coordination. These funds must be ring-fenced, inflation-adjusted, and released only after verified remediation. In parallel, host governments should mandate a global open-access registry, under platforms like the Extractive Industries Transparency Initiative (EITI) or the IAEA, to disclose uranium contracts, revenue sharing, compliance records, and community benefits, backed by donor conditions and international best practices.
    - *Desired Outcome:* Increased financial and legal accountability; reduced legacy pollution and corruption; greater trust between firms, governments, and communities.

8. Guarantee community representation and protect sites in armed conflict

    - Local communities, particularly Indigenous populations, are often excluded from meaningful participation in uranium governance, and uranium sites remain highly vulnerable during armed conflicts.
    - *Recommendation:* Legally require community representation in mining governance—through reserved decision-making roles, equity participation, and quotas for women and Indigenous leaders—by institutionalising a Common-Pool Resource model. This model ensures shared management responsibilities between the state, mining firms, and affected communities. In parallel, establish bilateral and multilateral protocols to protect uranium facilities during conflict, preventing their targeting or militarisation.
    - *Desired Outcome:* More equitable and collaborative resource governance, stronger community trust and stewardship, and reduced environmental and radiological risks during political instability or war.

Limited War, Unlimited Consequences: Integrating the Global Environmental Impact of Nuclear Conflict into Contemporary Deterrence Thinking

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Introduction

The post-Cold War era has ushered in a "third nuclear age,"[1] marked by nuclear modernisation, emerging nuclear states, and the erosion of arms control agreements. Yet, nuclear policies continue to overlook the catastrophic climate impacts of nuclear warfare, risks far surpassing the immediate devastation seen in Hiroshima and Nagasaki. The climate impacts of nuclear weapons use demand an interdisciplinary approach—one that strengthens the nuclear taboo by exposing their catastrophic environmental consequences. Traditional nuclear

1 Andrew Futter and Benjamin Zala, "Strategic Non-Nuclear Weapons and the Onset of a Third Nuclear Age," European Journal of International Security 6, no. 3 (2021): 257–277, https://doi.org/10.1017/eis.2021.2.

policies overlook these environmental risks, requiring climate scientists and policymakers to collaborate. A comprehensive risk assessment framework, improved crisis preparedness, and sustainable nuclear governance are crucial for ensuring resilience and global security in an era of climate-driven instability. This policy paper bridges the gap between nuclear strategy and climate science, urging the integration of environmental risks into deterrence and arms control. Using the case studies that apply the Whole Atmosphere Community Climate Model (WACCM), and analysing their findings, we demonstrate the catastrophic effects of nuclear war on climate, arguing for urgent doctrinal reforms to mitigate this existential threat. Without policy shifts grounded in climate science, the world risks an irreversible crisis.

Analysis

Contemporary Strategic Landscape: Increased Probability of a Nuclear War

Currently, states possessing nuclear weapons are all modernising their nuclear arsenals. For example, the United States' modernisation plan, costing at least $1.5 trillion, will revamp every aspect of its strategic nuclear forces, including the air, land and sea triad and the country's nuclear warhead and pit production capabilities.[2] This enables the continuation of the global nuclear stockpile's existence for at least the next fifty years.[3] The Forecasting Research Institute estimates a 5% chance that nuclear-related accidents will occur by 2045, killing about 10 million people.[4] Although total nuclear stockpiles are declining due to the dismantlement of old weapons, the Federation of American Scientists reports that the number of operational, ready-to-use warheads is actually increasing.[5] Several factors are making nuclear use more likely today than during the Cold War.

One of the strategies guiding these modernisations involves preparing for limited nuclear wars. Jeffrey Larson, Director of Research at the NATO Defense College, defined "limited nuclear war" as a conflict involving the use of a small number of nuclear weapons in a controlled manner to achieve specific objectives, or as a last resort when facing conventional defeat.[6] According to US military strategists, the limited use of nuclear weapon is plausible in various scenarios, such as signalling a willingness to escalate, ending conflicts where the US or its allies are in jeopardy, retaliating against chemical, biological, or substantial cyberattacks, or securing a nuclear state that has lost control of its weapons.[7] There are also concerns among strategic security researchers, practitioners and policy makers that advancements in warhead accuracy and lower-yield weapons could lower

2 Xiaodon Liang, "U.S. Nuclear Modernization Programs: Fact Sheets & Briefs," Arms Control Association, last reviewed August 2024, https://www.armscontrol.org/factsheets/us-modernization-2024-update.

3 Benoît Pelopidas and Sebastian Christopher John Verschuren, "Writing IR after COVID-19: Reassessing Political Possibilities, Good Faith, and Policy-Relevant Scholarship on Climate Change Mitigation and Nuclear Disarmament," Global Studies Quarterly 3, no. 1 (March 2023): https://doi.org/10.1093/isagsq/ksad006.

4 Bridget William et al., "Can Humanity Achieve a Century of Nuclear Peace? Expert Forecasts of Nuclear Risk," FRI Working Paper #4, October 29, 2024, https://static1.squarespace.com/static/635693acf15a3e2a14a56a4a/t/672541e94c430d6f5583a2f9/1730494967571/N.

5 Hans Kristensen et al., Status of World Nuclear Forces, Federation of American Scientists, March 29, 2024, https://fas.org/initiative/status-world-nuclear-forces/.

6 Jeffrey A. Larsen and Kerry M. Kartchner, eds., On Limited Nuclear War in the 21st Century (Stanford: Stanford University Press, 2014).

7 Bruce W. Bennett, "On US Preparedness for Limited Nuclear War," in On Limited Nuclear War in the 21st Century, ed. Jeffrey A. Larsen and Kerry M. Kartchner (Stanford: Stanford University Press, 2014), 211–243.; George H. Quester, "The End of the Nuclear Taboo?" in On Limited Nuclear War in the 21st Century, ed. Jeffrey A. Larsen and Kerry M. Kartchner (Stanford: Stanford University Press, 2014), 172–190.

the threshold for the use of nuclear arsenals.[8] Nuclear threats have been made both before and during Russia's aggression against Ukraine, and the situation remains dynamic as the conflict continues to unfold.[9] Reflecting a similar trend, Russia has also revised its nuclear doctrine, reportedly adopting a more permissive stance on nuclear weapon use in response to perceived threats. Russia's updated nuclear doctrine appears to broaden the conditions under which it might use nuclear weapons. Compared to the 2020 version, which limited nuclear use to threats against the state's 'very existence', the new policy allows for nuclear retaliation in response to conventional attacks considered a critical threat to its sovereignty or territorial integrity.[10]

The post-Cold War nuclear order is unravelling as great power competition intensifies. Direct confrontations involving nuclear-armed states (Russia-Ukraine, Israel-Gaza) and emerging technologies like cyber weapons[11] are creating unprecedented escalation risks.[12]

Withdrawal of the US and Russia from bilateral agreements, including the Intermediate-Range Nuclear Forces Treaty (INF Treaty) and others, is eroding the arms control regime. Further, Russia's 2023 withdrawal from the Comprehensive Test Ban Treaty (CTBT) has been a move that has, in the words of former US Secretary of State Antony Blinken, "only serve[d] to set back confidence in the international arms control regime."[13] There have also been calls by close aides to the Trump administration for renewing nuclear testing, a move that would end a more than thirty-year moratorium by the US.[14]

Case of US and Russia: Probability of Nuclear Exchange, Withdrawals from Arms Control Agreements and their Current Deterrence Thinking

Together, Russia and the US possess an inventory of approximately 10,624 out of the 12,121 nuclear warheads deployed and stored in the world.[15] Currently, the only bilateral treaty on arms control between the United States and Russia in force is the New Strategic Arms Reduction Treaty (New START). The agreement was signed in 2010 and entered into force in 2011 for ten years. In 2021, it was extended for five more years and is set to

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8 Hans Kristensen et al., Status of World Nuclear Forces, Federation of American Scientists, March 29, 2024, https://fas.org/initiative/status-world-nuclear-forces/.

9 Stephen Blank, "How Ukraine Reveals Russian Nuclear Strategy," Defense & Security Analysis 39, no. 3 (2023): 353–368, https://doi.org/10.1080/14751798.2023.2204595.

10 Daryl G. Kimball, Putin's Decision to Lower Threshold for Nuclear Use Is Irresponsible and Dangerous (Washington, D.C.: Arms Control Association, November 19, 2024), https://www.armscontrol.org/pressroom/2024-11/statement-putins-decision-lower-threshold-nuclear-use-irresponsible-and-dangerous.

11 Abdul Moiz Khan, "Cyberwarfare and New Pathways of Nuclear Escalation: Implications for South Asia," Journal of Security & Strategic Analyses 10, no. 2 (June 2024): 135–149, https://doi.org/10.57169/jssa.0010.02.0322. Christopher F. Chyba, "New Technologies & Strategic Stability," Daedalus 149, no. 2 (April 2020): 150–70, https://doi.org/10.1162/daed_a_01795.

12 Abdul Moiz Khan, "Cyberwarfare and New Pathways of Nuclear Escalation: Implications for South Asia," Journal of Security & Strategic Analyses 10, no. 2 (June 2024): 135–149, https://doi.org/10.57169/jssa.0010.02.0322. Christopher F. Chyba, "New Technologies & Strategic Stability," Daedalus 149, no. 2 (April 2020): 150–70, https://doi.org/10.1162/daed_a_01795.

13 "Russia Withdraws Ratification of Nuclear Test Ban Treaty | Arms Control Association," www.armscontrol.org, November 3, 2023, https://www.armscontrol.org/blog/2023-11/nuclear-disarmament-monitor.

14 William J. Broad, "Trump Advisers Call for U.S. Nuclear Weapons Testing If He Is Elected," The New York Times, July 5, 2024, sec. Science, https://www.nytimes.com/2024/07/05/science/nuclear-testing-trump.html.

15 Stockholm International Peace Research Institute, "Role of Nuclear Weapons Grows as Geopolitical Relations Deteriorate—New SIPRI Yearbook Out Now," press release, June 17, 2024, https://www.sipri.org/media/press-release/2024/role-nuclear-weapons-grows-geopolitical-relations-deteriorate-new-sipri-yearbook-out-now.

expire in 2026.[16] Both Washington and Moscow, under the treaty, committed to deploy no more than 1,550 strategic nuclear warheads and a maximum of 700 long-range missiles and bombers each. Also, each side can deploy no more than 800 intercontinental ballistic missiles.[17] However, in 2023, Russia announced that it would suspend its implementation of some provisions of the treaty. These include suspension of on-site inspection of nuclear facilities, refusal to meet the bilateral consultative commission, and ending data exchanges on the movement of delivery vehicles, launchers, and warheads.[18] The possibility of a new arms control agreement between the two states after the expiration of the New START in 2026 remains bleak. Withdrawal from most arms control treaties by the US and Russia confirms the lack of motivation and commitment to establish new treaties. If the New START expires, there will be even less control in the ongoing arms race between the US and Russia.

Nuclear Doctrine of the United States

According to the Nuclear Posture Review (NPR) 2022 of the United States, their declaratory policy is, "As long as nuclear weapons exist, the fundamental role of US nuclear weapons is to deter nuclear attack on the United States, our allies, and partners. The US would only consider the use of nuclear weapons in extreme circumstances to defend the vital interests of the United States or its allies and partners."[19] The United States has a first-use nuclear doctrine, nevertheless, it maintains that its bar of nuclear employment is very high and "there remains a narrow range of contingencies in which US nuclear weapons may still play a role in deterring attacks that have strategic effect."[20] The US has also developed integrated and tailored deterrence strategies to counter any kind of threat to itself or its allies.[21] Integrated deterrence refers to "the seamless combination of capabilities to convince potential adversaries that the costs of their hostile activities outweigh their benefits."[22] However, there is no mention of the implications of the use of nuclear weapons on the environment. The humanitarian agenda (addressing the humanitarian consequences of nuclear weapons use) should be incorporated into deterrence thinking of states to further strengthen the nuclear taboo and also encourage other states to follow suit.

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16 Nuclear Threat Initiative, "New START Treaty," accessed March 3, 2025, https://www.nti.org/education-center/treaties-and-regimes/treaty-between-the-united-states-of-america-and-the-russian-federation-on-measures-for-the-further-reduction-and-limitation-of-strategic-offensive-arms/

17 Al Jazeera and news agencies, "What Is the New START Nuclear Deal and Why Did Russia Suspend It?," February 22, 2023. https://www.aljazeera.com/news/2023/2/22/what-is-the-new-start-nuclear-deal-and-why-did-russia-suspend-it.

18 Anna Schumann, "New START: Frequently Asked Questions – Center for Arms Control and Non-Proliferation," Center for Arms Control and Non-Proliferation, March 3, 2023, https://armscontrolcenter.org/new-start-frequently-asked-questions/.

19 U.S. Department of Defense, 2022 Nuclear Posture Review Fact Sheet: U.S. Nuclear Deterrence Strategy and Policy, 2022 National Defense Strategy, accessed March 3 2025, https://www.defense.gov/Portals/1/Spotlight/2022/NDS/NUCLEAR%20STRATEGY%20AND%20POLICY%20-%20NPR%20Factsheet.pdf.

20 Center for Arms Control and Non-Proliferation, "2022 Nuclear Posture Review," accessed March 3 2025, https://armscontrolcenter.org/2022-nuclear-posture-review/.

21 https://www.defense.gov/News/News-Stories/Article/Article/3237769/official-says-integrated-deterrence-key-to-national-defense-strategy/

22 The White House, National Security Strategy (Washington, D.C.: The White House, October 12, 2022), 22, https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/11/8-November-Combined-PDF-for-Upload.pdf.

Contemporary Russian Deterrence Thinking

Russia has recently updated its nuclear doctrine, lowering the threshold of nuclear use. According to the decree signed by President Putin in November 2024, even non-nuclear weapon threats to Russia and its allies can trigger a nuclear response.[23] This has been a marked shift from the previous policy of only resorting to nuclear weapons when the "very existence of the state" was under threat. The new doctrine now reads that Russia "reserves the right" to respond to any nuclear attack or conventional attack that creates "a critical threat to the sovereignty and security of Russia or its ally Belarus.[24]The recent changes in Russian nuclear doctrine point towards its deterrence thinking that nuclear weapons can even be used to deter conventional threats. This can increase the possibility of nuclear use, especially in the context of the ongoing war in Ukraine.

Nuclear Winter: What Would It Look Like

Nuclear winter refers to the devastating environmental consequences of a nuclear war, which could lead to a prolonged period of global cooling, darkness, and drought.[25] Studies indicated that smoke from a nuclear war would rise into the stratosphere, where it would linger for 10–20 years, spreading globally and absorbing sunlight. This would heat the stratosphere and, while depleting the ozone layer, increase harmful ultraviolet radiation on Earth, and lead to heightened risks such as skin cancer, eye damage, and impaired plant photosynthesis. Meanwhile, the blockage of sunlight would cool the planet's surface, reduce precipitation, and severely disrupt agriculture, potentially triggering disease outbreaks and violent conflict.[26] Despite uncertainties in climate modelling, simulations "have consistently predicted nuclear winter as an outcome of nuclear war".[27] Even a regional nuclear war involving only a small fraction of current arsenals, such as 100 nuclear explosions with 15-kiloton yields, roughly the size of the Hiroshima bomb, could burn 1,300 square kilometres of urban areas and inject massive amounts of black carbon into the stratosphere. This smoke, made of light-absorbing elemental carbon and organics, would disrupt the global climate for years,[28] causing shorter agricultural growing seasons, reduced temperatures for up to 25 years, and dramatic declines in precipitation,[29] resulting in a "nuclear drought," and a widespread famine in already food-insecure regions like Sub-Saharan Africa, South Asia, and the Middle East.[30]

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23 Daryl G. Kimball, "Russia Revises Nuclear Use Doctrine," Arms Control Association, December 2024, https://www.armscontrol.org/act/2024-12/news/russia-revises-nuclear-use-doctrine.

24 Ibid.

25 Alan Robock, "Nuclear Winter," WIREs Climate Change 1, no. 3 (May/June 2010): 249–263, https://doi.org/10.1002/wcc.72.

26 Ira Helfand, Nuclear Famine: Two Billion People at Risk (International Physicians for the Prevention of Nuclear War, 2013), http://www.ippnw.org/pdf/nuclear-famine-two-billion-at-risk-2013.pdf.

27 Carlos Vega, "The Climate Blind Spot in Nuclear Weapons Policy," Bulletin of the Atomic Scientists, November 2, 2023, https://thebulletin.org/2023/11/the-climate-blind-spot-in-nuclear-weapons-policy/.

28 Veerabhadran Ramanathan and Gregory Carmichael, "Global and Regional Climate Changes Due to Black Carbon," Nature Geoscience 1, no. 4 (April 2008): 221–227, https://doi.org/10.1038/ngeo156.

29 Allison J. Liska et al., "Nuclear Weapons in a Changing Climate: Probability, Increasing Risks, and Perception," Environment: Science and Policy for Sustainable Development 59, no. 4 (July 2017): 22–33, https://doi.org/10.1080/00139157.2017.1325300.

30 Alan Robock and Owen B. Toon, "Local Nuclear War, Global Suffering," Scientific American 302, no. 1 (January 2010): 74–81.

In 2012, a UN report warned that even a limited nuclear war could cause climate disruption and famine for over a million people.[31] More recently, a research team led by Lili Xia[32] reinforced this, using advanced models to demonstrate how nuclear war-induced soot would devastate global food supplies, concluding that the probable trade restrictions, coupled with the above factors resulting from nuclear wars, "would be a global catastrophe for food security".[33]

Previous Studies on Climatic Impacts of Different Cases of Nuclear Exchange

The Whole Atmosphere Community Climate Model (WACCM) is a state-of-the-art Earth System Model (ESM) designed to simulate atmospheric processes from the surface to the thermosphere, incorporating interactions between chemistry, radiation, and Earth dynamics. Earth System Models (ESMs) like WACCM integrate multiple components of the climate system, including the atmosphere, ocean, land, and biosphere, to provide a comprehensive understanding of long-term environmental changes.

The academic literature includes multiple climate model simulations of soot released by nuclear exchange and its climatic impacts, with effects differing depending on the location and the scale of the conflict. A case study analyses the effects of a regional nuclear war using climate modelling to predict that 5 Tg of soot released into the stratosphere would drop the global temperature to about 1.5 degrees Celsius, lasting over a decade. This study also highlights substantial Ozone loss, disruption of monsoon cycles and long-term agricultural decline as a climatic impact of even a limited nuclear exchange.[34]

Another study predicts the climate impacts of a large-scale nuclear conflict, including the US and Russia's nuclear war scenario. The research conducted in the paper suggests that if 150 Tg of soot is injected into the atmosphere, there would be an immediate global temperature drop of 9 degrees Celsius with an extreme reduction in precipitation and sunlight for over a decade. Unlike the previous study, which focused on regional war impacts, this study emphasises near-total collapse of the global food system, prolonged ozone depletion resulting in harmful UV exposure and sea ice expansion to lower latitudes.[35]

In this case, a hypothetical large-scale US-Russia nuclear exchange is analysed by considering the findings of the previously conducted study. The compound effects of such an exchange will be rapid cooling, a projected 30% drop in global precipitation, and stratospheric Ozone loss within months of the conflict.[36] These conditions

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31 Alyn Ware and Riet van Riet, "The Climate–Nuclear Nexus," Pacific Ecologist, Summer 2013, https://pacificecologist.org/archive/22/pe22-climate-nuclear-nexus.pdf.

32 Lili Xia et al., "Global Food Insecurity and Famine from Reduced Crop, Marine Fishery, and Livestock Production Due to Climate Disruption from Nuclear War Soot Injection," Nature Food 3, no. 8 (August 2022): 586–596, https://doi.org/10.1038/s43016-022-00573-0.

33 Allison J. Liska et al., "Nuclear Weapons in a Changing Climate: Probability, Increasing Risks, and Perception," Environment: Science and Policy for Sustainable Development 59, no. 4 (July 2017): 591, https://doi.org/10.1080/00139157.2017.1325300.

34 William Burr, "Investigating the Climate Impacts of Nuclear War | National Security Archive," Gwu.edu, October 30, 2024, https://nsarchive.gwu.edu/briefing-book/climate-change-transparency-project-nuclear-vault/2024-10-30/investigating-climate

35 Joshua Coupe et al., "Nuclear Winter Responses to Nuclear War between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE," Journal of Geophysical Research: Atmospheres 124, no. 15 (August 8, 2019), https://doi.org/10.1029/2019jd030509.

36 Umair Irfan, "The World's Oceans Are Extremely Hot. We're about to Find out What Happens Next.," Vox, June 16, 2023, https://www.vox.com/climate/23762529/atlantic-ocean-record-heat-wave-el-nino-hurricane-climate-change.

affect fisheries, agriculture and human health globally, with sea ice expansion intensifying climate disruption.[37] This, coupled with soot-induced cooling and ozone depletion, would amplify risks across interconnected ecosystems even in non-belligerent regions.[38]

These environmental impacts strengthen the argument that nuclear war is not only a traditional security risk but also a human and environmental security hazard.[39] The previously conducted studies demonstrate the global, long-term climatic impacts of a limited and a full-scale nuclear war, underscoring why a rethinking of deterrence and prevention strategies must include climate security dimensions.[40]

Gaps in Current Deterrence Thinking

Contemporary deterrence strategies are rooted in Cold War-era logic, emphasising escalation control, second-strike capabilities, and counterforce targeting. These doctrines assume that nuclear deterrence preserves strategic stability by threatening adversaries with consequences of unacceptable damage, thereby preventing nuclear conflict. However, these strategies largely ignore that in the case of a nuclear conflict, the severity of climatic impacts can not be accurately predicted by science. These strategies also ignore the dynamics of emerging technologies, where wars are not fought on the ground but in other domains, including cyberspace, which introduces new vulnerabilities, such as manipulation of nuclear security systems. This, coupled with the potential threat of unstable leaders and potential use of nuclear weapons in a conflict triggered by either a cyberattack, miscalculation, or miscommunication, can have profound climatic impacts globally.

Scientific literature on nuclear winter used for this study suggests that even a limited exchange could trigger catastrophic climate implications. These impacts include immediate temperature drop, sea ice expansion, collapse of food production, and famine on a global scale. Despite this, nuclear policy discussions and deterrence strategies struggle to incorporate these climatic impacts in decision-making. Traditionally, deterrence, as it currently stands, functions on the assumption that nuclear conflict is containable within political and military terms, with little acknowledgement of its transnational environmental consequences, affecting an enormous area, including the states that are not even involved in the conflict.

The erosion of arms control agreements and the ongoing arms race between the US and Russia signal growing instability. These trends are both symptoms of and contributors to the deepening disconnect between deterrence frameworks and the scientific climatic realities of nuclear war. The failure to include environmental risks in nuclear decision-making reflects a critical gap in global deterrence thinking. Climate impacts are not just a peripheral concern, they are central to understanding the true costs and risks of nuclear weapons today.

A credible deterrence framework would need to fully integrate these environmental considerations and the current world dynamics. This would require a re-evaluation of nuclear doctrines, possibly transforming deterrence to incorporate all the impacts of nuclear war and the increasing possibility of such a war under the

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37 Umair Irfan, "El Niño Is Here, and It Could Become a Big One. Here's What It Means for Our Weather.," Vox, May 30, 2023, https://www.vox.com/climate/23738846/el-nino-2023-weather-heat-wave-climate-change-disaster-flood-rain.

38 Ayansina Ayanlade et al., "Extreme Climate Events in Sub-Saharan Africa: A Call for Improving Agricultural Technology Transfer to Enhance Adaptive Capacity," Climate Services 27 (August 2022): 100311, https://doi.org/10.1016/j.cliser.2022.100311.

39 Derek Smith, "Sea Ice's Cooling Power Is Waning Faster Than Its Area of Extent," Michigan News, University of Michigan, July 17, 2024, https://news.umich.edu/sea-ices-cooling-power-is-waning-faster-than-its-area-of-extent/.

40 Joshua Coupe et al., "Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE," Journal of Geophysical Research: Atmospheres 124 (2019): 8522-8543 https://doi.org/10.1029/2019JD030509.

current political and technological circumstances. This shift would open the door to alternative approaches grounded in shared human security and environmental sustainability, rather than mutual destruction. States must begin to include climate science in their security policies, arms control negotiations, and strategic risk assessments. This integration would reshape global nuclear discourse, pushing it toward a framework that is not only militarily rational but also environmentally acceptable.

Policy Recommendations

To address critical gaps in contemporary deterrence thinking and the growing risks of nuclear-climate impacts, this paper proposes six key recommendations.

1. Prohibit the Use of Nuclear Threats in Armed Conflict

   Nuclear threats, as exemplified by dangerous rhetoric in the Russia-Ukraine war, must be excluded from geopolitical conflicts. Even limited nuclear use could trigger severe climate consequences, making it vital to integrate climate risk into deterrence thinking and institutionalise norms against nuclear threats.

2. Institutionalise and Expand the UN Scientific Panel on Nuclear War Impacts

   The new UN General Assembly panel on the impacts of nuclear war offers a crucial opportunity to build a lasting, science-policy mechanism. Its findings should be institutionalised through regular reporting, scientific updates, and integration into First Committee processes. Transforming the panel into a permanent body could help ensure climate-informed deterrence by focusing on key areas such as: (1) modelling nuclear exchange scenarios,[41] (2) analysing atmospheric and oceanic effects,[42] (3) assessing food and health system risks,[43] and (4) evaluating regional vulnerabilities.[44] This would close the decades-long gap in international scientific oversight of nuclear-climate risks.

3. Strengthen the Climate-Nuclear Focus Across Key Multilateral Forums

   To integrate climate risks into nuclear deterrence thinking, multilateral forums should sharpen their focus on the nuclear-climate nexus through targeted, context-appropriate measures.

   - UNEP could host a time-bound expert group on extreme environmental disruptions, including nuclear winter, under its environmental security or disaster risk reduction frameworks.

41 Joshua Coupe et al., "Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE," Journal of Geophysical Research: Atmospheres 124, no. 15 (August 8, 2019), https://doi.org/10.1029/2019jd030509.

42 Charles G. Bardeen et al., "Extreme Ozone Loss Following Nuclear War Results in Enhanced Surface Ultraviolet Radiation," Journal of Geophysical Research: Atmospheres 126, no. 18 (September 24, 2021), https://doi.org/10.1029/2021jd035079.

43 Lili Xia et al., "Global Food Insecurity and Famine from Reduced Crop, Marine Fishery, and Livestock Production Due to Climate Disruption from Nuclear War Soot Injection," Nature Food 3, no. 8 (August 2022): 586–596, https://doi.org/10.1038/s43016-022-00573-0.

44 Carlos Vega, "The Climate Blind Spot in Nuclear Weapons Policy," Bulletin of the Atomic Scientists, November 2, 2023, https://thebulletin.org/2023/11/the-climate-blind-spot-in-nuclear-weapons-policy/.

- The UN Security Council should build on its climate-security mandate (Resolution 2349) by convening thematic debates on nuclear-climate disruption and its implications for international peace and security.
- The Conference on Disarmament should include regular scientific briefings on nuclear-related environmental risks to better inform disarmament negotiations.
- Regional organisations (e.g., ASEAN, AU, OAS) can identify vulnerabilities to nuclear-induced climate shocks and explore how resilience measures might align with existing climate adaptation or emergency preparedness strategies.

These efforts complement awareness-raising in broader climate forums and anchor nuclear risk in the technical and security institutions best placed to act.

4. Integrating Climate Impact Assessments into NPT Article 6 Implementation

The Nuclear Non-Proliferation Treaty (NPT) Review Conference member states should integrate climate impact assessments into Article 6 disarmament processes through three key measures:

- Establish a working group to develop climate-disarmament metrics, enabling nuclear states to demonstrate how arsenal reductions mitigate environmental risks.
- Require nuclear-weapon states to include climate impact assessments in their regular reporting under a strengthened review process, particularly in disarmament-related sections.
- Commission expert studies within the NPT framework to identify which weapons systems pose the greatest environmental threat, informing disarmament prioritisation.

This approach would make climate security a measurable component of non-proliferation compliance while maintaining the NPT's verification framework.

5. Integrate Climate Risk into Strategic Stability and Risk Reduction Frameworks

Nuclear-armed states—both NPT and non-NPT—should adapt their strategic doctrines to account for climate-related drivers of instability and crisis escalation. Specifically:

- P5 states should lead efforts to incorporate climate stressors into ongoing strategic stability dialogues, with regular briefings on how environmental shocks (e.g., extreme weather, food insecurity) may increase the likelihood of miscalculation or conflict involving nuclear-armed states.
- All nuclear-armed states should adopt risk reduction measures, such as clarifying nuclear use doctrines, narrowing launch conditions, and enhancing crisis communication, that explicitly address how climate-induced instability could undermine deterrence credibility.
- States negotiating new arms control frameworks should include non-nuclear strategic threats (e.g., cyberattacks on nuclear command and control, AI-driven escalation) and consider how these interact with climate disruption to challenge deterrence assumptions.

By integrating climate risk into both reassurance strategies and arms control frameworks, nuclear states will contribute to reducing the likelihood of nuclear weapons use, thereby improving global security for all.

Conclusion

A fundamental reassessment of nuclear deterrence thinking by states and international organisations is necessary to address the existential risks posed by even a limited nuclear exchange. Current deterrence frameworks overlook the long-term climatic consequences of nuclear use, such as nuclear winter, which undermines arms control credibility and raises the risk of miscalculated escalation. To mitigate these risks, nuclear deterrence strategies must be revised to acknowledge the environmental and humanitarian consequences of nuclear war. Expanding scientific research, integrating climate considerations into international security dialogues, and reinforcing multilateral arms control agreements are critical steps toward a more responsible nuclear strategy.

Nuclear Testing and Displacement in the Pacific: Integrating Transitional Justice into the Nuclear Justice Framework

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Note to Reader

As this anthology neared completion, a report from the Institute for Energy and Environmental Research revealed that U.S. officials had asked the Bikinians to leave their homeland in 1946 without disclosing that nuclear tests were already planned. The report also details the lasting impacts of this displacement on the Marshallese.[1]

1 Arjun Makhijani, The Legacy of U.S. Nuclear Testing in the Marshall Islands, Institute for Energy and Environmental Research, May 2025.

Introduction

The impact of the displacement of people, including Indigenous and native communities, by nuclear testing is an oft-neglected aspect of nuclear harm. Nuclear harm is a wide-ranging concept that encompasses immediate and long-term impacts of nuclear weapons on human life and the environment. The displacement of people is one aspect of nuclear harm, which is often inextricable from other harms. Using the displacement of Pacific Islanders as a result of nuclear testing carried out by the United States (US) between 1946 and 1958 as a case study, this paper seeks to set out an analytical framework for the integration of transitional justice into the nuclear justice framework. It identifies the communities or peoples displaced by the Pacific Islands tests and assesses the extent to which these communities have realised nuclear justice against an integrated framework. The latter part of the paper will set out specific recommendations for addressing gaps in remediation and reparation, such as the establishment of a scientific advisory body to make context-specific recommendations for nuclear justice, reassessment of the parameters of the compensation system, and modelling of reparation processes on other successful processes. Such an approach can go some way towards achieving the aims of transitional justice, including establishing the truth, ensuring justice, providing reparations, guaranteeing non-recurrence, and preserving memory.

Integrated Analytical Framework for Justice

Nuclear Justice and Transitional Justice

The concept of nuclear justice refers to efforts to address the harm, inequalities, and rights violations that result from the development, testing, deployment, and legacy of nuclear weapons, especially as they have affected marginalised and Indigenous communities, contaminated environments, hindered socioeconomic development, and harmed current and future generations.[2] As a framework, nuclear justice is a critical lens that examines how the development of nuclear weapons intersects with histories of nuclear colonialism, nuclear imperialism, racial capitalism, and other concepts.[3] The nuclear justice framework includes several core components: historical and structural analysis; the centring of affected communities; environmental justice; intergenerational

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2 Jana Baldus, Caroline Fehl, and Sascha Hach, Beyond the Ban: A Global Agenda for Nuclear Justice, PRIF Report No. 4/2021 (Frankfurt am Main: Peace Research Institute Frankfurt, 2021), 1; United Nations General Assembly, Addressing the Legacy of Nuclear Weapons: Providing Victim Assistance and Environmental Remediation to Member States Affected by the Use or Testing of Nuclear Weapons, A/C.1/79/L.74 (2024), https://docs.un.org/en/A/C.1/79/L.74.

3 Leila Hennaoui and Marzhan Nurzhan, "Dealing with a Nuclear Past: Revisiting the Cases of Algeria and Kazakhstan through a Decolonial Lens," The International Spectator 58, no. 4 (2023): 91–109, https://doi.org/10.1080/03932729.2023.2234817. See also Haleema Saadia et al, 'The Ultimate Coloniser: Challenging Racism and White Supremacy in Nuclear Weapons Policy Making' in BASIC's Emerging Voices Network (EVN) Anthology: De-siloing Existential Threats: Challenging Identity, Power, and Inclusivity in the Nuclear Policy Field, July 2023, 36–46, https://basicint.org/wp-content/uploads/2023/07/Anthology_De-siloing-Existential-Threats_A4-2-1.pdf ; Exequiel Lacovsky, "Opposing Nuclear Weapons Testing in the Global South: A Comparative Perspective," The International Spectator 58, no. 4 (December 2023): 73–90, https://doi.org/10.1080/03932729.2023.2270899.

and intersectional justice; abolitionism, accountability, and reparations.[4] Individual and collective financial compensation for victims, as well as the remediation of contaminated environments, are key elements of nuclear justice.[5]

Transitional justice is increasingly viewed as a framework through which the legacy of nuclear weapons tests can be addressed in a victim-centred manner.[6] Scholars have advocated for a more integrated approach to nuclear justice that situates the concept within the broader context of global social inequalities.[7] Transitional justice involves the coming together of people to address the legacies of horrendous atrocities or to end recurring cycles of violent conflict, by developing a range of responses in the form of processes or mechanisms to achieve the pillars of justice. There are five pillars of transitional justice. Also known as dimensions of nuclear justice, they include (i) truth seeking; (ii) justice; (iii) reparations; (iv) memorialisation; and (v) guarantees of non-recurrence.[8] The authors of this paper believe these concepts can be contextualised to assess and analyse how the displacement of Indigenous communities in the Marshall Islands as a result of nuclear testing can be addressed. Having defined transitional justice, this section lists its key dimensions and outlines the mechanisms for achieving it. It then applies these to nuclear justice to create an analytical framework for assessing

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4 Baldus, Fehl, and Hach, Beyond the Ban, 8; Barbara Rose Johnston and Holly M. Barker, Consequential Damages of Nuclear War: The Rongelap Report (Walnut Creek, CA: Left Coast Press, 2008); Shannon Cram, Unmaking the Bomb: Environmental Cleanup and the Politics of Impossibility, vol. 14 (Oakland: University of California Press, 2023); Traci Brynne Voyles, Wastelanding: Legacies of Uranium Mining in Navajo Country (Minneapolis: University of Minnesota Press, 2015); Mari Faines, "No Justice Is Possible without Studying the Injustices of Nuclear Weapons," Bulletin of the Atomic Scientists, February 2, 2023, https://thebulletin.org/2023/02/no-justice-is-possible-without-studying-the-injustices-of-nuclear-weapons/; Hugh Gusterson, People of the Bomb: Portraits of America's Nuclear Complex (Minneapolis: University of Minnesota Press, 2004); J. Höffken and M. V. Ramana, "Nuclear Power and Environmental Injustice," WIREs Energy and Environment 13, no. 1 (2024): e498, https://doi.org/10.1002/wene.498.

5 Treaty on the Prohibition of Nuclear Weapons (TPNW), adopted 7th July 2017, entered into force 22nd January 2021, article 6. United Nations Office for Disarmament Affairs, Treaty on the Prohibition of Nuclear Weapons, https://disarmament.unoda.org/wmd/nuclear/tpnw/.disarmament.unoda.org+2.

6 Baldus, Fehl, and Hach, Beyond the Ban, 8; Peace Boat, "Recommendations from Japanese Civil Society on Articles 6 and 7 of the Treaty on the Prohibition of Nuclear Weapons,", https://peaceboat.org/english/news/TPNW1MSP-JP.; Office of the United Nations High Commissioner for Human Rights (OHCHR), A/HRC/57/77: Addressing the Challenges and Barriers to the Full Realization and Enjoyment of the Human Rights of the People of the Marshall Islands, Stemming from the State's Nuclear Legacy – Report of the Office of the United Nations High Commissioner for Human Rights – Advance Edited Version, https://www.ohchr.org/en/documents/thematic-reports/ahrc5777-addressing-challenges-and-barriers-full-realization-and.

7 Jana Baldus, Caroline Fehl, and Sascha Hach, "NPT 2022: An Opportunity to Advance Nuclear Justice," Global Policy, May 13, 2022; Asia-Pacific Leadership Network, Understanding Nuclear Justice for the Pacific: Expert Insights, September 7, 2023, https://aplne.net/understanding-nuclear-justice-for-the-pacific-expert-insights/ ; Patrick Kaiku, "Nuclear Justice for the Marshall Islands in the Age of Geopolitical Rivalry in the Pacific," Asia-Pacific Leadership Network, August 21, 2023, https://cms.apln.network/wp-content/uploads/2023/08/Patrick-Kaiku_August-2023.pdf; Republic of the Marshall Islands National Nuclear Commission, Nuclear Justice for the Marshall Islands: A Strategy for Coordinated Action FY2020–FY2023 (Majuro: National Nuclear Commission, 2019), https://rmi-data.sprep.org/system/files/RMI%20NNC%20Strategy%202019.pdf; Denisa Muhameti, Pursuing Nuclear Justice: Confronting Unequal Impacts on Minorities (Munich: ICAN Germany, November 2023), https://www.icanw.de/wp-content/uploads/2023/11/ICAN-Deutschland-2023-Nuclear-Justice-Englisch-2.pdf; Leila Hennaoui, Towards Nuclear Justice: A Global South Perspective (Munich: ICAN Germany, November 2023), https://www.icanw.de/wp-content/uploads/2023/11/ICAN-Deutschland-2023-Nuclear-Justice-Englisch-2.pdf.

8 United Nations Human Rights Council, International Legal Standards Underpinning the Pillars of Transitional Justice, A/HRC/54/24 (July 10, 2023), https://documents.un.org/en/A/HRC/54/24.

displacement, one of the many harms that the Indigenous people of the Pacific Islands suffered in consequence of US nuclear testing.

An Integrated Approach

This paper is not the first attempt to integrate transitional justice and nuclear justice in the study of nuclear harms. An earlier example of this integration, which informed this paper, is found in the work of researchers Baldus, Fehl and Hach at the PRIF Leibniz-Institut für Friedens- und Konfliktforschung in 2021. In their work, they use concepts existing in transitional justice to recommend policies that ensure accountability, justice and reconciliation are achieved for victims of nuclear weapons testing and development.[9] However, their work did not focus on contextualising each pillar and mechanism to the case of nuclear weapons and their harm. One of the theoretical contributions of this paper is therefore the contextualisation of these concepts, as defined by the UN Human Rights Council, within the framework of nuclear justice.

Truth

Truth refers to "the inalienable right of victims and their families to know the truth about past events concerning the perpetration of heinous crimes and about the circumstances and reasons that led, through massive or systematic violations, to the perpetration of those crimes."[10] In the context of nuclear weapons harm, this would mean that affected communities have the right to know the full extent of harm caused, including health, environmental, and intergenerational aspects, as well as political and strategic decisions that led to enabling the practice of conducting testing, and displacing communities. In this sense, a thorough and truthful narrative of the history of nuclear weapons development and testing helps set the ground for justice.

Justice

Justice refers to "the legal obligation to prosecute and punish violations while removing obstacles that would prevent the fulfilment of that obligation."[11] In the context of nuclear justice, this involves the challenging task of holding states and individuals accountable, potentially even criminally accountable, for the harms caused by nuclear weapons. This is particularly challenging given the lack of established legal frameworks for prosecuting nuclear-related harms. In fact, Baldus et al. mention this pillar of transitional justice and its related mechanisms as the least developed and least applicable to nuclear justice.

Reparation

Reparation involves "the general duty of States to provide remedy to victims of human rights violations and breaches of international humanitarian law."[12] This is the pillar most developed in the context of nuclear justice, which involves the nuclear-possessing states' obligation to acknowledge and address the suffering caused by their nuclear activities through providing monetary compensation, health monitoring or medical assistance, and environmental remediation.

Memorialisation

Memorialisation includes "transmitting to present and future generations, accurate and comprehensive accounts of past human rights violations." The goal of memorialisation is to restore dignity, promote healing and reconciliation, and lay the groundwork for achieving the last pillar of transitional justice. For nuclear justice, this would involve documenting and publicly and officially acknowledging the devastating human and environmental

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9 Baldus, Fehl, and Hach, Beyond the Ban; United Nations Human Rights Office, Transitional Justice and Human Rights, https://www.ohchr.org/en/transitional-justice.

10 United Nations Human Rights Council, International Legal Standards Underpinning the Pillars of Transitional Justice, 4.

11 United Nations Human Rights Council, International Legal Standards Underpinning the Pillars of Transitional Justice, 9.

12 United Nations Human Rights Council, International Legal Standards Underpinning the Pillars of Transitional Justice, 12.

consequences of nuclear activities. These efforts serve not only to honour victims but also foster social awareness and build momentum for the prevention of recurrent harm.

Guarantees of non-recurrence

Lastly, guarantees of non-recurrence refer to ensuring "that victims do not have to again endure violations of their rights," with the goal of "breaking structural causes of societal violence."[13] In the context of nuclear weapons, arguably, this requires dismantling systems that allow the continued possession, development, and potential use of nuclear weapons, in addition to preventing activities such as nuclear testing.

It is noteworthy that while each of these pillars and mechanisms often overlap and intersect; they can also be broken down into distinct elements, with a view to providing an all-encompassing approach to justice. Although it is beyond the scope of this paper to define each pillar and its elements in depth, the authors have used the above descriptions to guide their analysis.

United States Nuclear Testing in the Pacific

The Marshall Islands comprise twenty-nine coral atolls that humans have occupied since the second millennium BC. In 1947, the United Nations (UN) grouped the Marshall Islands with other island nations as the Trust Territory of the Pacific Islands (TTPI), placing them under the administration of the US.[14] Because of their remoteness, the US considered the islands ideal for nuclear weapons testing. Since the TTPI was far from continental land, it was hoped that the radioactive fallout would fall into the Pacific Ocean.[15] Moreover, ideal climatic conditions prevailed in the Marshall Islands. Lastly, the islands, being only sparsely populated (though by no means uninhabited), allowed the US to conduct its tests without massive resistance. The trusteeship agreement on the TTPI became effective on 18th July 1947, giving the US "full powers of administration, legislation, and jurisdiction over the Territory."[16] In turn, the US promised to promote the economic, social, and educational advancement of its inhabitants. The local population had no say and was instead subjected to a foreign power.

As early as 1946, before the US' trusteeship, the first US nuclear exercise took place at Bikini Atoll, an island group belonging to the Marshall Islands.[17] In a series of tests known as Operation Crossroads, two atomic bombs were detonated in July 1946. Between 1946 and 1958, the US conducted 67 nuclear tests – 23 tests in the Bikini Atoll and 44 tests in the Enewetak Atoll – totalling approximately 108,5 megatons.[18] The US conducted its largest nuclear detonation ever, Castle Bravo, the most powerful thermonuclear weapon, at Bikini Atoll

13 United Nations Human Rights Council, International Legal Standards Underpinning the Pillars of Transitional Justice, 18.

14 Gregory J. Trifonovitch, "Trust Territory of the Pacific Islands," in Linguistics in Oceania, 2nd ed., ed. J. Donald Bowen, 1063–1087 (Berlin; Boston, MA: De Gruyter Mouton, 2019). The other island nations within the Trust Territory included what is now known as, Palau, Federated States of Micronesia, and the US Commonwealth of the Northern Mariana Islands.

15 Keith M. Parsons and Robert A. Zaballa, Bombing the Marshall Islands: A Cold War Tragedy (Cambridge: Cambridge University Press, 2017), 14.

16 United Nations, 1947, S/318, Article 3, 2.

17 Keith M. Parsons and Robert A. Zaballa, Bombing the Marshall Islands: A Cold War Tragedy (Cambridge: Cambridge University Press, 2017).

18 Parsons and Zaballa, Bombing the Marshall Islands; Daryl Kimball and Chris Rostampour, "US, Marshall Islands Grapple with Nuclear Legacy," Arms Control Today, November 2022, https://www.armscontrol.org/act/2022-11/news/us-marshall-islands-grapple-nuclear-legacy.

on 1st March 1954.[19] Accordingly, the Marshall Islanders from the Enewetak and Bikini Atolls were the most disproportionately affected communities by US testing.

Affected Community: Marshall Islanders from the Bikini Atoll

Prior to Operation Crossroads, the 167 Indigenous inhabitants of Bikini had to be evacuated. The Bikini inhabitants were relocated to the atoll of Rongerik, a much smaller group of islands. Within two months, the Bikinians suffered from food shortages and ran out of water. In 1948, due to malnourishment and the possibility of starvation, they were relocated to a temporary camp on Kwajalein Island, after which they were moved to Kili Island. However, Kili lacked natural resources and fishing opportunities compared to Bikini Atoll.[20] Once again, the islanders suffered from food scarcity. Having been led to believe that a return to Bikini was possible, the islanders were reluctant to adapt to the changed physical conditions on Kili and to abandon their traditional harvesting and fishing methods. These hopes of an early return were soon dashed as the US continued its tests until 1958, leaving the island in ruins.

However, the Bikinians in exile were unwilling to give up their homeland. They continued to campaign for their rights, leading the US authorities to declare the radiation on Bikini harmless in 1969.[21] Hence, a small portion of the population was permitted to return home, only to be evacuated again in 1978. This time, however, exile was to become permanent. Although the US Atomic Energy Commission (AEC) had conducted radiological cleanups on Bikini in the 1960s, it was not until the 1970s that the first medical examinations and radiological surveys took place in the TTPI. The dangers of radioactive contamination on Bikini became scientifically apparent for the first time. Through the consumption of food grown in the island's radioactive soil, US scientists concluded that the Bikinians "may have ingested the largest amount of radiation of any known population […] and that it was necessary to move the people off this island as soon as possible."[22] Thus, in 1978, the islanders were removed from their home island for a second time. Since then, no one has been allowed to return to Bikini, which remains contaminated and uninhabitable to this day.

Affected Community: Marshall Islanders from the Enewetak Atoll

In December 1947, four months after the Trusteeship Agreement had gone into effect, the US announced that Eniwetok Atoll would be closed for security reasons until further notice, as permitted by Article 13 of the Trusteeship Agreement. Acting through the AEC, the US intended to "conduct necessary experiments relating to nuclear fission" on Eniwetok.[23] Permanent resettlement was necessary for the 145 inhabitants; moreover, the US promised to compensate the Indigenous people for their land.[24] In truth, however, a fate similar to that of the Bikinians awaited the islanders.

A total of six test series were conducted on Eniwetok, starting with Operation Sandstone and the detonation of three nuclear bombs in 1948. For this purpose, the native population was relocated to Ujelang, an island half the

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19 L. April Brown, "No Promised Land: The Shared Legacy of the Castle Bravo Nuclear Test," Arms Control Today, March 2014, https://www.armscontrol.org/act/2014-03/no-promised-land-shared-legacy-castle-bravo-nuclear-test.

20 Leonard Mason, From a Time of Starvation to a Time of Hope: The Relocation of the Bikini Marshallese (University of Hawai'i at Manoa, 1988).

21 Jack Niedenthal, "History of the People of Bikini Following Nuclear Weapons Testing in the Marshall Islands: With Recollections and Views of Elders of Bikini Atoll," Health Physics 73, no. 2 (1997).

22 Jonathan M. Weisgall, "The Nuclear Nomads of Bikini," Foreign Policy, no. 39 (June 1980): 89f., https://doi.org/10.2307/1148413.

23 United Nations, 1947, S/613, 1.

24 United Nations, 1947, S/613, 1f.

size of their home island and with a much smaller bay that did not have enough fish to sustain the inhabitants. Like the Bikini residents, the Eniwetok inhabitants were later, in 1980, allowed to return to their home island after a radiological cleanup had been carried out on the atoll. To their dismay, the main island, Runit, remained inaccessible. Instead, the island had been converted into a repository for radiation-contaminated waste. The so-called Cactus Dome on Runit was what had made the resettlement possible in the first place: Originally a crater from an atomic bomb in 1958, the US had filled said hole with radioactive soil and waste from all the other islands and capped it with concrete slabs.[25] To this day, Runit remains closed. On their return, the islanders also found that Elugelab Island had been completely wiped out.[26] The island had been destroyed as part of Operation Ivy, which tested the world's first actual hydrogen bomb in 1952, providing another example of how nuclear weapons would leave a lasting mark on the TTPI.

Impacts/Effects of Testing on Displacement and from Displacement

Nuclear testing in the Pacific Islands has had severe and lasting consequences. These consequences have caused displacement and/or resulted from displacement. The intense heat from the tests killed marine life instantly; for example, oil from nine sunken ships destroyed delicate coral ecosystems in Bikini Atoll lagoon.[27] Many atolls remain uninhabitable due to high radiation levels and contaminated food and water sources. For the Marshallese, forced relocation had devastating economic consequences. The US assumed island communities could be easily moved. However, unfamiliarity with the community's needs and land—or deliberate neglect—left them heavily dependent on unreliable US resource shipments. New lands were often infertile and lacked sustainable food supplies.[28] Secondary displacements isolated the displaced Marshallese, making it nearly impossible to raise awareness of their plight.

Radiation exposure caused immediate burns and radiation sickness. At the same time, long-term effects – congenital disabilities, cancer, miscarriages and genetic disorders – devastated the Pacific Islanders,. This detrimental legacy of testing was compounded by subsequent unethical human experimentation. A week after the Castle Bravo test, the US launched a medical study on the effects of radiation on the Marshallese while providing medical care to the people who were exposed to high levels of radiation. The effort, called Project 4.1, has been criticised because researchers did not acquire informed consent from the Marshallese who participated.[29] In 1965-66, scientists with the AEC secretly injected the Enewetakese with radioactive chromium-51 and made them drink tritium-laced water.[30] Alongside physical effects, the psychological consequences of US testing have proved profound, with high rates of mental health disorders across the region.[31] Even today, a deep-seated distrust of Western medicine and science persists. Critically, this leads to reluctance to seek treatment for the disproportionately high cancer rates, exacerbated by the fact that such treatments often involve radiation therapy.[32]

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25 Michael B. Gerrard, "America's Forgotten Nuclear Waste Dump in the Pacific," The SAIS Review of International Affairs 35, no. 1 (2015).

26 Parsons and Zaballa, Bombing the Marshall Islands, 45.

27 Parsons and Zaballa, Bombing the Marshall Islands, 45.

28 M. Smith-Norris, Domination and Resistance: The United States and the Marshall Islands during the Cold War (Honolulu: University of Hawaii Press, 2016).

29 National Museum of Nuclear Science & History, "Marshall Islands," Atomic Heritage Foundation, https://ahf.nuclearmuseum.org/ahf/location/marshall-islands/; Brown, "No Promised Land".

30 Smith-Norris, Domination and Resistance.

31 Rohan Patel, "Aftermath of Nuclear Testing in the Pacific Islands," American Society of Clinical Oncology, 2024, 1–3.

32 Patel, "Aftermath of Nuclear Testing".

Before the de-facto US occupation, the Marshall Islands were a largely matrilineal society, with land rights passing through the female line. The Islands faced cultural disruption, with the Marshallese women suffering disproportionately from the health impacts of nuclear testing. The Indigenous communities also report more intangible wounds, such as disrupted traditions and a lingering sense of humiliation at the hands of the US.[33]

Pursuit of Justice

The US has not met its legal obligations under the Trusteeship System.[34] In 1954, after the Bravo incident, the UN Trusteeship Council received a petition from the Marshallese demanding that “all experiments with lethal weapons in this area be immediately ceased.”[35] Subsequently, in response and contrary to their wishes, the Trusteeship Council granted the US official permission to continue nuclear testing.[36]

The Pacific Islanders’ legal campaign for justice began in the 1980s, with lawsuits filed in US courts, leading to a settlement under the Compact of Free Association (COFA) (effective 1986), an agreement between the US and the Marshall Islands. Notably absent from this agreement is an explicit reference to “justice”. Historically, the US has disavowed ongoing responsibility for enduring harms stemming from over a decade of nuclear testing. This seems contrary to the truth-telling pillar of transitional justice. Section 177 established a $150 million Nuclear Fund to settle all claims “past, present and future” and established a Nuclear Claims Tribunal.[37] This tribunal arguably falls within the justice and reparations pillars of transitional justice. While the Tribunal ruled against the US government in multiple cases, it quickly ran out of funds.[38] The US-Marshall Islands agreements provide a potential avenue for nuclear justice, particularly with the 2023 Memorandum of Understanding (MOU), which includes provisions for addressing the health and environmental impacts of the tests.[39] The MOU provides for improving accessibility to documents and information relating to the US nuclear testing programme, as well as a museum and research facility on that testing programme.[40] The museum will contribute to the memorialisation pillar by preserving the memory of nuclear testing and fostering understanding of its impacts.

While the US considers the issue of nuclear justice to be settled and is likely to refuse further engagement on this issue, efforts to compensate the Pacific Islanders have fallen short of meeting demands from the affected communities.[41] The partial payments and limited funding and support for medical and radiological

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33 B. Unal, P. Lewis, and S. Aghlani, The Humanitarian Impacts of Nuclear Testing (International Security Department, 2017).

34 S. Marcoux, “Trust Issues: Militarisation, Destruction, and the Search for a Remedy in the Marshall Islands,” Columbia Human Rights Law Review, January 9, 2021, https://hrlr.law.columbia.edu/hrlr-online/trust-issues-militarization-destruction-and-the-search-for-a-remedy-in-the-marshall-islands/.

35 United Nations, 1954, T.PET.10/28, 2.

36 United Nations, 1954, T.PET.10/28, 1.

37 Compact of Free Association (2003), US Department of State, 14–15, https://2009-2017.state.gov/documents/organization/173999.pdf.

38 D. Pevec, “The Marshall Islands Nuclear Claims Tribunal: The Claims of the Enewetak People,” Denver Journal of International Law and Policy 35, no. 1 (2006): 222.

39 Daryl G. Kimball, “US, Marshall Islands Sign Deal on Nuclear Testing Impacts,” Arms Control Today, https://www.armscontrol.org/act/2023-03/news/us-marshall-islands-sign-deal-nuclear-testing-impacts.

40 Kimball, “US, Marshall Islands Sign Deal”.

41 While COFA negotiations were formalised in 2023, the Marshall Islands continues to bring up the issue of nuclear justice. See, for instance: Greenpeace International, “On Marshall Islands Remembrance Day, Greenpeace Calls for Nuclear Justice and Reparations from the United States,” March 1, 2025, https://www.greenpeace.org/international/press-release/73100/on-marshall-islands-remembrance-day-greenpeace-calls-for-nuclear-justice-and-reparations-from-the-united-states/; Shaghayegh Chris Rostampour, “U.S. Formalizes Agreements With the Marshall Islands,” Arms Control Today, April 2023, https://www.armscontrol.org/act/2023-11/news/us-formalizes-agreements-marshall-islands.

monitoring do not address issues such as health, displacement, or loss of infrastructure in ways that would satisfy the Marshallese. Many Marshallese are still displaced because of radiological contamination and suffer from radiation-related cancers, congenital disabilities and poor health due to the destruction of agriculture. Campaigners argue that the broader impact of US use and testing has not been addressed, and that the compensation framework should be broadened.[42]

Contemporary efforts for nuclear justice continue through national initiatives, lobbying the US Congress, working with international organisations, and raising awareness. The Marshall Islands co-sponsored a 2016 UN General Assembly (UNGA) resolution to negotiate an instrument prohibiting nuclear weapons, namely the Treaty on the Prohibition of Nuclear Weapons (TPNW), advocating for the "rights of survivors of nuclear detonation".[43] International bodies have also provided forums for reparation and recognition efforts. In 2022, the UN Human Rights Council adopted a resolution calling for the US to provide compensation, capacity-building, and technical assistance to Pacific Islanders.[44] In addition, nationally, the Marshall Islands National Nuclear Commission (NNC), an independent statutory authority, was established in 2017 to spearhead efforts for nuclear justice. It has adopted a strategy that aligns with the pillars of transitional justice.[45]

Policy Recommendations: A Transitional Justice Approach to Nuclear Justice

This section sets out proposals for policy actions in the immediate and long term to meet the pillars of justice as defined by the transitional and nuclear justice frameworks, namely, truth, justice, reparations, guarantees of non-recurrence, and memorialisation. Given that these pillars overlap and intersect, pursuing one without the other is not possible. It is important to note that the paper's authors do not see it appropriate to suggest a single conceptualisation of what just settlement will look like for displaced peoples without including their voices. The participation and inclusion of impacted communities, as well as the impartiality and neutrality of mechanisms, are crucial for achieving justice as described by the transitional justice framework. The following measures, if carried out with the inclusion of impacted communities and conducted impartially, could be a starting point that can be broadened to achieve a settlement that impacted communities could consider adequate and just.

1. Acknowledge the Truth about Nuclear Testing and Its Impact on Affected Communities

   The US should acknowledge the truth of how its nuclear testing, including its human experimentation studies in the Marshall Islands, has violated the rights of Indigenous communities. Any diplomatic efforts concerning the Marshall Islands should acknowledge the harms done to the Indigenous populations. Furthermore, civil societies and policymakers alike must cultivate an understanding

42 Nuclear Justice, "Comparison of Compensation Systems: Seeking Justice," https://nuclear-justice.net/comparison/.

43 United Nations Office for Disarmament Affairs, Treaty on the Prohibition of Nuclear Weapons, Articles 6 and 7; ICAN, "Marshall Islands," https://www.icanw.org/marshall_islands.

44 UN OHCHR, "Human Rights Council Adopts 14 Resolutions," Press Releases, October 7, 2022, https://www.ohchr.org/en/press-releases/2022/10/human-rights-council-adopts-14-resolutions-extends-mandates-ethiopia-burundi.

45 "Republic of the Marshall Islands Environment Data Portal | Information for Decision Making," accessed February 7, 2025, https://rmi-data.sprep.org/resource/nuclear-justice-marshall-islands-coordinated-action-justice. The Strategy for Coordinated Action emphasises capacity building, healthcare, education and awareness, and environmental concerns; however, it has placed insufficient focus on the displacement of these communities and their denial of other fundamental rights associated with their ancestral land.

of the harms done as a result of nuclear testing as a process centred on the individuals and the communities whose rights and interests have been disproportionately and enduringly harmed. This has to be promoted both at the political level and among the public debate first through truth-seeking commissions beyond the Nuclear Claims Tribunal, support for local educational efforts such as the Marshall Islands Educational Initiative and investing in US-sponsored educational programs, media campaigns, and cultural documentation, and ensuring that the narratives of affected communities are part of mainstream discourse.[46]

Given the harm experienced by the Indigenous communities in the Marshall Islands, it is imperative to form an expert-based scientific advisory body to offer context-specific solutions to realise nuclear justice. This body could be modelled after the Scientific Advisory Group established under the TPNW to look at the humanitarian consequences of nuclear risk and verification-related issues. This will also be consistent with the recent UNGA efforts to establish a panel of scientific experts to study the effects of nuclear war.[47]

2. Create a "Truth & Claims Commission" empowered to hear Marshallese testimonies, recommend reparations, and co-manage former test-site areas as living memorials

   There should be a genuine inquiry into Indigenous communities' experiences that focuses on the historical and current impact of nuclear tests and deployment on native land. The recorded inquiries and findings of this body should be disseminated to the international community to bring back dignity to Indigenous communities harmed in the process. A key foundation for truth-telling is ensuring transparency and public access to information, particularly at the national level; this, in turn, could help achieve memorialisation. The 2023 MOU between the US and the Marshall Islands, which provides for improving accessibility to documents and information relating to the US nuclear testing programme, as well as a museum and research facility on the programme, is a step in the right direction. It will be important to ensure the participation of the indigenous affected communities, such that their perspectives and experiences are also taken into account.

   New Zealand's Treaty of Waitangi settlements provide a potential model.[48] Central to this approach is the establishment of an independent, Indigenous-informed body, like the Waitangi Tribunal, to hear and assess claims of historical harm, particularly those stemming from nuclear testing. Such a body in the Marshallese context could provide a formal platform for truth-telling, recommend context-specific reparations, and ensure that Indigenous experiences are central to policy making. As in New Zealand, negotiated settlements could include not only financial compensation but also co-management of affected lands, official apologies, and cultural redress through memorialisation initiatives. This is also in line with the NNC's efforts to achieve nuclear justice.

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46 Marshallese Educational Initiative, Marshallese Educational Initiative, https://www.mei.ngo/. See also Maren Vieluf et al, 'Strengthening the Humanitarian Impacts Agenda: Nuclear Education and Raising Nuclear Awareness within the NPT' in BASIC's Emerging Voices Network (EVN) Anthology: Strengthening the Humanitarian Impacts of Nuclear Weapons Agenda within the NPT, BASIC, May 2024, pp. 21-26, https://basicint.org/wp-content/uploads/2024/06/Strengthening-the-HINW-agenda-within-the-NPT.pdf

47 Reaching Critical Will, "New UN Panel Will Study the Effects of Nuclear War," Reaching Critical Will, November 12, 2024, https://www.reachingcriticalwill.org/news/latest-news/17267-new-un-panel-will-study-the-effects-of-nuclear-war.

48 Richard S. Hill, "Ngā Whakataunga Tiriti – Treaty of Waitangi Settlement Process," Te Ara – The Encyclopedia of New Zealand, accessed May 10, 2025, https://teara.govt.nz/en/nga-whakataunga-tiriti-treaty-of-waitangi-settlement-process.

3. Advance Reparative Justice Through Inclusive and Expanded Compensation Frameworks

   The full realisation of reparations and compensation to Indigenous groups harmed by nuclear testing and development requires a reassessment of the parameters of the damage compensation system for displaced individuals and communities.[49] This should entail the clarification of criteria to establish the relationship between exposure and harm, as well as eligibility for compensation. Schemes should be revised to eliminate restrictive proof thresholds for victims, acknowledging the multidimensional health, psychological, social, and longitudinal, immediate, long-term, and cross-generational effects of nuclear testing. Broadening the compensation framework will allow the full humanitarian impact of nuclear weapons use, including social and intergenerational consequences, to be addressed. In this regard, the impacts of displacement, including the loss of the intangible relationship to land and cultural traditions, can also be accounted for.

4. Reform Bilateral/ Multilateral Engagements for Inclusive and Comprehensive Nuclear Justice

   It is important for the US to continuously reform its relationship with the Marshall Islands. The COFA was a starting point for decolonisation. However, the currently established relationship between the US and the Marshall Islands is far from guaranteeing non-recurrence of harm. In this regard, first and foremost, the Marshall Islands should continue advocating for nuclear justice on all fronts. Second, the US should make an effort to address nuclear harms in ways that meet the demands of the Marshallese impacted by its former government's actions. Last but not least, in relevant fora where justice for the Marshall Islands is discussed, other state actors should put to ensure that inclusive diplomacy is being practised. Inclusive diplomacy through integrating displaced communities' representatives in policy negotiations on victim assistance and remediation allows for multiple, layered identities and experiences to be heard and considered.[50] These discussions are necessary for the realisation of comprehensive and equal remediation and assistance to displaced communities.

5. Build Durable Guarantees of Non-Recurrence through Political Reform, Inclusive Governance, and Nuclear Disarmament Commitments

   A first step toward guaranteeing the non-recurrence of displacement of Pacific Islanders due to US nuclear activities was discontinuing testing, even though the decision to halt nuclear testing was not made to achieve this goal. Since then, however, there has been limited action to address the structural and institutional drivers that enabled these harms. Although the COFA is a step toward decolonisation, continued military dominance over affected territories, lack of Indigenous political representation, and an opaque decision-making process over US nuclear policy mean that we are far from guaranteeing that further harm will not occur. Meaningful guarantees of non-recurrence would involve political reform, legal safeguards, and the inclusion of Pacific Islanders' voices in nuclear governance. Lastly, non-recurrence would not be possible without the pursuit of disarmament and abolition of nuclear weapons, an obligation that the US, as a party to the Non-Proliferation Treaty, has taken upon itself.

49 Peace Boat, "Recommendations from Japanese Civil Society", 17.

50 Baldus, Fehl, and Hach, Beyond the Ban, 8.

Conclusion

There is much to be done to address the legacy of the displacement of people due to the use and testing of nuclear weapons. This paper focused on one case study, the US tests in the Marshall Islands, but its analysis can be applied to other cases of nuclear testing. It highlights the importance of acknowledging nuclear harms through an integrated analytical framework that integrates transitional justice in nuclear justice. While recognising the limitations of this paper's authors in resolving the problem and proposing a framework of settlement for displaced peoples that would fully address their needs, the policy recommendations present a starting point toward justice. The recent discourse around the resumption of nuclear testing and the continued existence and modernisation of US nuclear weapons are all insults to those harmed by the legacies of nuclear testing.[51] The only true guarantee of non-recurrence of nuclear harms is the abolition of all nuclear weapons.

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51 Rebecca Hersman and Joseph Rodgers, "U.S. Nuclear Warhead Modernization and 'New' Nuclear Weapons," Center for Strategic and International Studies, December 11, 2020, https://www.csis.org/analysis/us-nuclear-warhead-modernization-and-new-nuclear-weapons; Arms Control Association, "U.S. Nuclear Modernization Programs," Arms Control Association, last reviewed August 2024, https://www.armscontrol.org/factsheets/us-modernization-2024-update.

Expanding the Definition of Atomic Veterans to Redress Harms to Service People in Nuclear Missions

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Note to Reader

Unless otherwise stated, the term 'Atomic Veteran' in this paper refers to the official current definition found in the Radiation Exposure Compensation Act (RECA). The definition is explored in detail below.

Introduction

Many of the nuclear-armed states have exposed their service personnel to radiation risks during nuclear testing. This paper focuses on the United States, though many of the issues and recommendations are likely to be applicable to other nuclear-armed states. In the US, the term 'Atomic Veteran' has hitherto been limited and lacks a forward-looking component. The primary purpose of the current definition is to identify individuals who are qualified to claim medical treatments and compensation. A stronger and more compelling definition of Atomic Veterans would be: 1) more inclusive of all individuals who were exposed to radiation while serving their country, 2) more historically accurate and detailed concerning nuclear testing, 3) consistently updated, relevant, and in alignment with federal laws, and 4) acknowledging exposure risks and harms. This paper will focus on analysing the failings of the current definition to explain why it needs to be reconceptualised in a more inclusive approach.

Since the 1970s and 1980s, the term Atomic Veteran has been used by the United States Department of Veterans Affairs (VA) to designate individuals whose health has been impacted by radiation exposures. An Atomic Veteran is defined as a person "who, as part of his or her military service: participated in an above-ground nuclear test between 1945–1962; or was part of the US military occupation forces in/around Hiroshima/Nagasaki before 1946; or was held as a POW in or near Hiroshima or Nagasaki"[1]. This definition was established in the Radiation Exposed Veterans Compensation Act of 1988 (H.R. 1811), passed on May 20, 1988, as a result of public pressure.

The US current definition of Atomic Veterans is limited in scope. Notably, it excludes military personnel who were exposed and continue to be exposed to unsafe levels of radiation, not necessarily from above-ground nuclear tests, but from working with nuclear materials and depleted uranium munitions. Not only does a high level of radiation exposure cause physical harm, but there is a large psychological component affecting mental health, which vastly expands the scope of atomic veterancy writ large.

However, the term Atomic Veteran is often used more broadly and colloquially to convey the notion of members of the armed forces (the Army, Marine Corps, Navy, Air Force, Space Force, and the Coast Guard in the case of the United States) who have experienced health issues related to radiation exposure. This paper takes the position that all service members, their dependents, and individuals who were inadvertently exposed to nuclear radiation, risks, and harms should be formally included in the official definition.

Methodology and Initial Discussion

This paper begins with a brief analysis of the Nevada Test Site (NTS) case study and US redress schemes. The NTS is where the US has conducted the majority of its nuclear tests (1951-1992). While atmospheric tests stopped in 1962 and underground tests ceased in 1992, testing has continued at the site in the form of subcritical tests: explosive tests on quantities of fissile material below the threshold for achieving a critical mass. This paper will focus on the NTS, an emphatic example of the harms suffered by people and the primary impetus for the term Atomic Veteran in its current legal definition.

Expanding the definition of Atomic Veterans would help connect the experiences of new veterans with past generations and conceptualise the harm they have sustained. The expansion of the term would bring greater focus to the enormity of the harm of working with nuclear weapons and the resultant long-term effects that radiation exposure has on any given population as a whole. By being more inclusive, historically accurate, and acknowledging nuclear risks and harms due to exposure, a more expansive definition would recognise the true scale of the impact on military and non-military individuals who have been affected by radiation. Lastly, it would widen the eligibility criteria for service people and others present at or near nuclear testing sites to be considered for compensation and reduce the high rejection rates of claims.

1 US Department of Veterans Affairs – Veterans Health Administration, "Are YOU An Atomic Veteran?" 2012, accessed 20 April, 2025, https://www.publichealth.va.gov/docs/radiation/atomic-veteran-brochure.pdf

The US Case of Nuclear Testing and the Term "Atomic Veteran"

Between World War II and the 1960s, over 200,000 US service members participated in atmospheric nuclear tests and cleanup operations. Tens of thousands of military members who met the definition of Atomic Veteran worked in the NTS,[2] where testing began in 1951 and ended in 1992, with an eventual 928 nuclear tests occurring.[3] Atmospheric tests stopped in 1962 with the signing of the Partial Test Ban Treaty (PTBT), although underground testing continued up until 1992. The increased cancer rates of Atomic Veterans led to the establishment of compensation schemes such as the Radiation Exposed Veterans Compensation Act (REVCA).[4]

Service members who participated in atmospheric nuclear tests were not provided with adequate protection, had no access to decontamination procedures, and were often unaware they had even been exposed to radiation.[5] Studies have found that cancer rates for service members were higher than the general population, and they were also more likely to die from cancer, with one study specifically finding that "soldiers at NTS had a death rate for leukaemia that was 50 percent higher than other groups of military personnel who did not work with atomic testing."[6] Additionally, the lack of decontamination procedure implementations led to fatal consequences. This was partially linked to the lack of understanding of nuclear harm and its extent.

The US government also examined the psychological effects on military members subject to nuclear explosions. The lack of prior knowledge and exposure to the immense heat and pressure of nuclear tests left some psychologically traumatised.[7] Furthermore, they were forbidden from speaking about their experiences for decades, under threats of fines and charges of treason.[8] Atomic Veterans who were on nuclear missions lack access to their classified medical records and radiation exposure doses, hindering their ability to receive compensation and appropriate medical care. Without access to their complete service and medical records, Atomic Veterans who have experienced adverse health outcomes lack the precise details of their exposure and the results of any medical examinations they may have received in the aftermath. The state of the US medical system also impacted health outcomes for service members, many of whom had difficulties obtaining and maintaining employment and thus often lost access to health insurance. Service members can seek medical care through the VA, but for Atomic Veterans, the lack of access to their complete medical records, combined with the overtaxed bureaucracy of the VA, often led to rejection or delayed approval for their treatments.

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2 Alex Wellerstein, "Atomic Soldiers: Training for the Final War," At the Brink (podcast), August 30 2023, accessed 2 March, 2025, https://atthebrink.org/podcast/atomic-soldiers/

3 Atomic Heritage Foundation, "Nevada Test Site," accessed 2 March 2025, https://ahf.nuclearmuseum.org/ahf/location/nevada-test-site/

4 Melinda F. Podgor, "The Inability of World War II Atomic Veterans to Obtain Disability Benefits: Time Is Running Out On Our Chance To Fix The System," The Elder Law Journal Vol. 13 (2006), p. 520—552, https://publish.illinois.edu/elderlawjournal/files/2015/02/Podgor.pdf

5 Georgetown University Bioethics Archive, "Advisory Committee on Human Radiation Experiments – Final Report," accessed 2 March, 2025, https://bioethicsarchive.georgetown.edu/achre/final/report.html

6 The Associated Press, "Testing in Nevada Deserts is Tied to Cancers," The New York Times, 26 October, 1999, https://www.nytimes.com/1999/10/26/health/testing-in-nevada-desert-is-tied-to-cancers.html

7 Jennifer LaFleur, "Atomic Vets," Retro Report, 29 May, 2016, https://retroreport.org/video/atomic-vets/

8 Atomic Heritage Foundation, "Atomic Veterans 1946-1962," accessed 2 March, 2025, https://ahf.nuclearmuseum.org/ahf/history/atomic-veterans-1946-1962/#_ftn21

US Redress Schemes Related to Radiation Exposure

Above-ground atmospheric testing all but ceased for the US in the 1960s as a result of the Partial Test Ban Treaty. Testing would continue at the NTS, but only underground and later in the form of subcritical testing. All the while, public pressure mounted as veteran groups lobbied state and federal government officials throughout the 1960s and 1970s to address the harms that occurred primarily at the NTS. These efforts culminated in an irregular patchwork of legislation intended to assist downwinders, uranium miners, victims of exposure to other types of unconventional weapons, and Atomic Veterans. The three relevant acts were the Veterans' Dioxin and Radiation Exposure Compensation Standards Act (VDRECSA) 1984, the Radiation Exposed Veterans Compensation Act (REVCA) 1988, and the Radiation Exposure Compensation Act (RECA) 1990.

The Veterans' Dioxin and Radiation Exposure Compensation Standards Act (VDRECSA) 1984

VDRECSA ensures that Atomic Veterans are entitled to disability compensation if they have had disabilities resulting from radiation exposure in atmospheric nuclear tests or occupation of Hiroshima or Nagasaki. The act requires the VA to establish guidelines, standards, and criteria for adjudicating compensation claims for radiation exposure disabilities of Atomic Veterans. The burden of proof is on the veteran, and it is often difficult to establish the service connection, making it difficult to obtain compensation under this act.

The Radiation Exposed Veterans Compensation Act (REVCA) 1988

REVCA presumes 13 specified diseases to be service-connected. The eligible "Atomic Veterans" are defined as those who participated onsite at an above-ground nuclear test, participated in the occupation of Hiroshima or Nagasaki, or were exposed to radiation as prisoners of war in Japan. Subsequent amendments of REVCA and Veteran Administration (VA) policy changes have increased the number of compensable diseases from 13 to 21. Congress repealed the Nuclear Radiation and Secrecy Agreements Act in 1996, so that Atomic Veterans are permitted to discuss their duties to establish service connection without fearing penalties.

The Radiation Exposure Compensation Act (RECA) 1990

RECA does not require eligible individuals to establish a causal relation between their diseases and radiation exposure. Instead, meeting the eligibility criteria presumes effects of radiation exposure. Eligible individuals are classified into three categories: (1) uranium employees who worked in a covered uranium mine in specified states from 1942-1971; (2) onsite participants who were at above-ground nuclear tests; and (3) individuals who lived downwind from the Nevada Test Site and are affected by the radioactive fallout emitted by the tests. They are entitled to a one-time lump sum compensation, and claims can be made by a specified surviving family member if an eligible individual is deceased. In June 2024, RECA officially expired, and only claims postmarked on and before June 11, 2024, will be filed and adjudicated.[9]

In effect, these three laws were drafted to achieve a single end: restitution for Atomic Veterans. While an exact amount spent on these programs is difficult to ascertain, approximately $2.6B has been approved on RECA payouts as of January 2023.[10] The mutual exclusivity of these programs means that veterans are unable to seek aid through multiple programs. The acts for these programs were first proposed in the 1970s, and by the time they were passed in 1988 and 1990 by the US Congress, they had been through many iterations. The resultant acts are insufficient to fully address the health issues caused by testing at the NTS.

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9 US Department of Justice Civil Division, "Radiation Exposure Compensation Act," Updated 24 April 2025, accessed 24 April 2025, https://www.justice.gov/civil/common/reca

10 US Department of Justice Civil Division, "Awards To Date 01/13/2023," Updated 13 January 2023, accessed 10 May 2025, https://web.archive.org/web/20230117051652/https://www.justice.gov/civil/awards-date-01132023

Discussion

Testing at the NTS raises questions about indirect state violence against its citizens, especially its service members. What limits should be placed on that violence, and where does responsibility lie when those limits are exceeded? Citizens and veterans have very limited redress against the state. How can accountability function in these cases?

These compensation schemes serve many purposes, and have different meanings for different people, which are contestable and not set in stone. The three redress schemes are the product of complex and contested political processes. Despite the substantial costs of these programs, their existence does not constitute future harm reduction, and they cannot be allowed to justify the creation of future Atomic Veterans and the continued cycle of harm against service members.

The current definition of Atomic Veteran is also exceptionally arbitrary, narrowly defining who qualifies, and fundamentally tethering the term to the NTS. This is problematic because, for people who will inevitably be exposed to radiation harms from nuclear weapons in the future, it will be tenuous and difficult for them to use the current framework to build upon the case of previous Atomic Veterans and receive restitution from the government.

Hence, it is important to expand the formal definition of Atomic Veterans to be more inclusive of all individuals who were exposed to radiation, particularly while serving their country. It should also be made more historically accurate and detailed regarding nuclear testing, consistently updated and relevant, and acknowledge exposure risks and harms. Moreover, it should not be tied to the NTS, so that future Atomic Veterans would be protected and have access to medical care.

These schemes would go some way to addressing harms, but we also need to prevent future harms. One way to do so is through treaties such as the Comprehensive Test-Ban Treaty (CTBT), which has a unique structure requiring Annex II countries to ratify it for its entry into force. Unfortunately, for the CTBT, it is this very structure that continues to stand in the way of the treaty's implementation and the full operationalisation of the Comprehensive Test-Ban Treaty Organisation, including on-site inspections, which constitute a crucial element for verifying that nuclear testing is not taking place.[11]

11 Daryl Kimball, "Comprehensive Test Ban Treaty at a Glance", Arms Control Association, July 2024, https://www.armscontrol.org/factsheets/comprehensive-test-ban-treaty-glance

Recommendations

1. The US should redefine the term Atomic Veteran to be more inclusive of all individuals who were exposed to radiation while serving their country, more historically accurate, and more detailed concerning nuclear testing. Moreover, this new definition should consistently be updated, relevant, and in alignment with federal laws. This includes acknowledging exposure risks and harms not just from nuclear testing, but also from occupational exposure, use of depleted uranium, and environmental contamination from nuclear materials. This change would allow for future Atomic Veterans, as more broadly defined, to access medical treatment and to claim remuneration. The new definition would also provide a comprehensive norm relating to the acceptable exposure of nuclear weapons and the arbitrary limits of state violence on its citizenry.

2. Along with this expansion of the definition, the government should release information about testing locations and test dates during which they were exposed to nuclear risks and harms, while updating relevant laws, particularly regarding compensation, as more information becomes known or available, either through declassification of information or the conduct of studies.

3. The next step would be to advocate for the adoption of this definition internationally. With the broader definition of Atomic Veterans enshrined in the US, other states should draw on their example and follow their lead.

4. Additionally, since RECA has lapsed, its reintroduction and indefinite extension would allow all people impacted by the NTS an opportunity to apply for benefits. The current wording of RECA includes a formal acknowledgement of harm. Considering the changing world security environment, nuclear-armed states should acknowledge that their service members were harmed in the process of acquiring such power.

5. These proposed changes to RECA, along with an amendment to declassify service members' medical records, would allow them to receive targeted healthcare services with information on the radiation exposure they received. Declassifying medical records remains a relevant goal as the burden of proof is placed on veterans advancing claims to seek compensation.

Limitations and Conclusion

Throughout its progression, this paper has sought to argue the need for a more inclusive, historically accurate, detailed, consistently updated, and relevant definition of Atomic Veterans that acknowledges exposure risks and harms while respectfully honouring individuals' service. This was advocated for through the lens of the US experience, particularly the NTS. While this paper is specific to the US, expanding the definition of Atomic Veterans can benefit other geographical locations and is important to assess and quantify nuclear harm accurately, to address and redress it.

The limitations of currently existing US compensation schemes are rooted in the lack of historical accuracy and detail. Throughout the years, the US government has failed to keep detailed records of all individuals present at nuclear test sites, especially in the early days of nuclear testing. This has translated into a limited understanding of the exact numbers of present personnel at nuclear testing sites and the levels of radiation to which they were exposed. This poor record-keeping, coupled with apparent concerns for national security, failed to account for all service members exposed to nuclear risks and harms. Consequently, it led to a failure to remedy and redress these harms for those exposed to them.

Knowledge gaps or limited knowledge about the short and long-term impacts of nuclear weapons testing, particularly at the time of these tests, led to a failure in accounting for these risks and in pre-empting them or developing proper prevention or risk reduction measures. This is consistent with the need for a more inclusive and consistently updated definition of Atomic Veterans, which acknowledges exposure risks and harms and honours service members and their service. Additionally, throughout the years, there has been an increased consensus around the need for ethics related to scientific undertakings, including nuclear testing, ultimately leading to a better definition of what these ethics should look like (and currently look like) and what constitutes appropriate risk.

List of Acronyms

ADS	Accelerator Driven System
AEC	US Atomic Energy Commission
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
CESM	Community Earth System Model
COFA	Compact of Free Association
CTBT	Comprehensive Test Ban Treaty
DDML	Data-Driven Machine Learning
DGR	Deep Geological Repository
EBR-II	Experimental Breeder Reactor II
ESG	Environmental, Social, and Governance
ESM	Earth System Model
EU	European Union
FR	Fast Reactor
HHRA	Human Health Risk Assessment
HLW	High-Level Waste
HTGR	High-Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
IFNEC	International Framework for Nuclear Energy Cooperation
ILW	Intermediate-Level Waste
ISL	In Situ Leaching
ITER	International Thermonuclear Experimental Reactor

LL-L/ILW	Long-Lived Low- and Intermediate-Level Waste
LLFPs	Long-Lived Fission Products
LLW	Low-Level Waste
LWR	Light Water Reactor
MA	Minor Actinides
ML	Machine Learning
MOU	Memorandum of Understanding
MSR	Molten Salt Reactor
MYRRHA	Multi-purpose Hybrid Research Reactor for High-tech Applications
NEA	Nuclear Energy Agency
NNC	Marshal Islands National Nuclear Commission
NPR	Nuclear Posture Review
NPT	Nuclear Non-Proliferation Treaty
NTS	Nevada Test Site
NWS	Nuclear weapon state
OECD	Organisation for Economic Co-operation and Development
OHCHR	Office of the United Nations High Commissioner for Human Rights
P&T	Partitioning and Transmutation
PTBT	Partial Test Ban Treaty
PWR	Pressurised Water Reactor
R&D	Research and Development
RECA	Radiation Exposure Compensation Act
REVCA	Radiation Exposed Veterans Compensation Act
ROI	Return on Investment
SDGs	Sustainable Development Goals
SFR	Sodium-cooled Fast Reactor

SMR	Small Modular Reactor
START	Strategic Arms Reduction Treaty
TPNW	Treaty on the Prohibition of Nuclear Weapons
TRISO	Tri-structural Isotropic
TTPI	Trust Territory of the Pacific Islands
TWG-FR	Technical Working Group on Fast Reactors
UF6	Uranium Hexafluoride
UN	United Nations
UNGA	United Nations General Assembly
VAUS	Department of Veterans Affairs
VDRECSA	Veterans' Dioxin and Radiation Exposure Compensation Standards Act
WACCM	Whole Atmosphere Community Climate Model

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Runit dome from the air, 1980 (US Department of Defence/Public Domain)

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Onkalo nuclear waste repository in Finland under construction, 2020 (Posiva)

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Tailing ponds at the Olympic Dam uranium mine, South Australia (www.nuclear-heritage.net, licensed under Creative Commons Attribution-Share Alike 4.0)

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Wreckage of a Douglas DC-3 in Sólheimasandur, Iceland, 2016 (Flickr/mhx, licensed under Creative Commons Attribution-NonCommercial-NoDerivs 2.0)

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US 'Crossroads Baker' nuclear test, Bikini Atoll,1946 (US Department of Defence/Public Domain)

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Staff at the Nevada Test Site, October 1979 (US Department of Energy/Public Domain)

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