POLICY FORUM

NUCLEAR SECURITY

The weapons potential of high-assay low-enriched uranium

Recent promotion of new reactor technologies appears to disregard decades-old concerns about nuclear proliferation

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Preventing the proliferation of nuclear weapons has been a major thrust of international policymaking for more than 70 years. Now, an explosion of interest in a nuclear reactor fuel called high-assay low-enriched uranium (HALEU), spurred by billions of dollars in US government funding, threatens to undermine that system of control. HALEU contains between 10 and 20% of the isotope uranium-235. At 20% ^{235}U and above, the isotopic mixture is called highly enriched uranium (HEU) and is internationally recognized as being directly usable in nuclear weapons. However, the practical limit for weapons lies below the 20% HALEU-HEU threshold. Governments and others promoting the use of HALEU have not carefully considered the potential proliferation and terrorism risks that the wide adoption of this fuel creates.

Commercial reactor fuels typically have low enrichments, in the range of 3 to 5% ^{235}U. At these enrichments, the fuel cannot sustain an explosive chain reaction. This has prevented nations or terrorists from simply repurposing commercial reactor fuel for weapons. Above around 6% ^{235}U, the fuel can sustain a fast chain reaction at normal density, but the mass needed for a weapon would be prohibitively large. Producing fuel with higher ^{235}U concentrations reduces the mass needed for a weapon to practical levels, but doing so requires enrichment capabilities that are controlled by only a small handful of countries. This arrangement effectively blocks most nations from modifying fresh nuclear reactor fuel to make weapons.

For technical reasons, the traditional 3 to 5% fuel will not suffice for many of the power reactor designs that nuclear engineers want to build today. For example, proposed microsized reactors are so inefficient with their neutrons that they need HALEU simply to turn on. Most designers favor 19.75% ^{235}U HALEU—on the cusp of HEU—because more ^{235}U almost always eases constraints, but use of HEU is discouraged because of its clear weapons potential. In many designs, the amount of HALEU needed is hundreds to thousands of kilograms, which may mean that a single reactor contains enough HALEU to make a nuclear weapon. If this is the case, commercializing HALEU fuels without ensuring that the material is appropriately protected against diversion by national governments or theft by terrorists would pose a serious threat to security.

> **“...computational tools that facilitate weapons design have spread around the world, placing greater importance on controlling nuclear materials...”**

In 1954, the US government’s weapons laboratory at Los Alamos performed studies to assess the weapons utility of uranium of various enrichments (*1*). The issue at the time was the proliferation potential of proposed exports of research reactors to foreign nations under the Atoms for Peace program. Using the information from Los Alamos, the US Atomic Energy Commission (AEC) concluded that fuels enriched to <10% ^{235}U were not weapons usable, regardless of the quantity. However, between 10 and 20% ^{235}U, the materials were of “weapon significance” and could be used in a nuclear weapon if available in sufficient quantity. On the basis of this assessment, the AEC allowed uranium exports of up to 20% ^{235}U—in part because it was concerned about the higher cost of reactors using fuel with lower enrichments—provided that the quantities were below the threshold of weapon significance.

In the mid-1960s, the AEC organized a new study to establish a technical basis for domestic nuclear material accountancy and security requirements (*2*). This ultimately led the agency to develop security rules for domestic users that contained an exemption for any quantity of uranium enriched below 20% ^{235}U. In 1979, a 20% lower limit on the enrichment of uranium considered to be weapons usable was adopted by the US Nuclear Regulatory Commission (NRC) in its rule on physical protection.

Why the AEC, and later the NRC, issued regulations that appear to disregard the findings related to HALEU from the original Los Alamos weapons laboratory study is unclear because the details remain classified. However, in 1984, J. Carson Mark, head of the Los Alamos Theoretical Division responsible for designing nuclear weapons from 1943 until 1973, confirmed in congressional testimony that HALEU was weapons usable down to 10% ^{235}U (*3*).

Several factors appear relevant to the creation of the loophole for HALEU. Historically, HALEU was only rarely used and limited mainly to research reactors. It would not have been practical to make a weapon from the small quantities used in a single research reactor, and regulators held that it was implausible that simultaneous thefts from multiple research reactors would occur. It was also the case that the AEC’s perspective on safeguards was established by a panel of industry representatives who believed that the future would be powered by nuclear reactors fueled with plutonium (*4*). In such a world, the additional risk from HALEU might have seemed insignificant because plutonium is a much more attractive bomb material. However, that world never emerged. The geological abundance of uranium turned out to be more than originally predicted, and uranium’s considerably more-favorable economics won the day.

Over the past few decades, the situation has evolved. Information and computational tools that facilitate weapons design have spread around the world, placing

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greater importance on controlling nuclear materials that were previously viewed as being of marginal utility. This, combined with recent proposals for increasing the use of HALEU in quantities that far exceed those required in the past, means that the time has come to review policies governing the use of this material.

The weapons potential of HALEU can be examined using the Serber-Bethe-Feynman formula (*5*). It relates the potential explosive yield to the spherical radius of an initial supercritical mass, the radius at which the mass becomes subcritical during explosive expansion, the rate of growth of the neutron chain reaction, and scaling constants with exact values that are determined from classified nuclear weapons tests but can be roughly approximated from the properties of unclassified systems. Although simple, the formula is famously reliable (*6*). Estimates of the inputs to the formula using a variety of open sources (including published critical mass and kinetics parameter data for different enrichments and core-reflector combinations) indicate that HALEU above about 12% ^{235}U could be used to make a practical weapon. These assessments indicate that quantities ranging from several hundred kilograms to about 1000 kg of 19.75% HALEU could produce explosive yields similar to or greater than that of the 15 kilotons of TNT equivalent bomb that the United States dropped on Hiroshima, Japan, at the end of World War II.

Designing such a weapon would not be without its challenges, but there do not appear to be any convincing reasons why it could not be done. The amount of nuclear material would be large compared with traditional weapons but not prohibitively so. Our extreme example of 1000 kg constitutes a metal ball with a diameter of 46 cm (18 inches). The neutron reflector and assembly mechanism would be added to this, but even so, the final size and weight might be acceptable if the weapon were delivered using an airplane, a delivery van, or a boat sailed into a city harbor.

A second challenge relates to a phenomenon called preinitiation, which could cause a substantial reduction in explosive yield. This occurs when neutrons emitted spontaneously by uranium-238, the dominant isotope in HALEU, initiate a nuclear chain reaction in the bomb core before the moment of maximum reactivity. This problem is much worse for reactor-grade plutonium, which has a spontaneous neutron emission rate about 300 times as high as that of 15% HALEU when scaled to the bare critical masses for the two materials. Even so, reactor-grade plutonium has been used successfully to make bombs (*7*), and the US Department of Energy (DOE) has said that: "At the lowest level of sophistication, a potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that)" [(*8*), p. 38]. This indicates that the preinitiation problems of HALEU can be overcome. Although preinitiation may have a bigger impact on some designs than others, even those that are sensitive to it could still produce devastating explosive power.

If the weapons usability of HALEU is borne out, then even a single reactor would pose serious security concerns. Yet, the DOE and US Department of Defense are providing funds for more than 10 reactor concepts with cores containing from several hundreds to many thousands of kilograms of HALEU, including the Natrium reactor being developed by TerraPower, a company founded by Bill Gates (*9*).

The 20% statutory division between HALEU and HEU has been interpreted as the technical threshold between weapons-usable and -nonusable uranium by generations of nuclear professionals. There was therefore little concern when, in 2018, the US nuclear power industry's lobbying organization, the Nuclear Energy Institute (NEI), pushed the US government to make more than a hundred tons of HALEU available annually by late this decade (*10*). Congress responded in the 2020 Energy Act, directing the DOE to share HALEU with private companies. In October 2020, the DOE announced a 50% cost-sharing program, providing up to $4 billion in federal funds to two demonstration reactors that plan to use multiton quantities of HALEU

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fuel. The Inflation Reduction Act of 2022 then appropriated $700 million to develop civilian supplies of HALEU, and Congress has since made available $2.72 billion more to subsidize the private production of LEU, including HALEU (*11*).

Now, other countries are starting to follow suit. The United Kingdom announced in January that it would be the first European nation to subsidize HALEU production (*12*), and France announced that it is looking into production options. Although the US NRC has recently determined that "Supplemental security measures…may be required to address the current threat environment and the changing understanding of the risks associated with [HALEU]" (*13*), to our knowledge, there has been no adequate evaluation of the risk to international security posed by HALEU in the quantities required by power reactors.

Given the stakes, we recommend that the US Congress direct the DOE's National Nuclear Security Administration to commission a fresh review of HALEU proliferation and security risks by US weapons laboratory experts. This study should take into consideration advancements in modeling, simulation, and nuclear-explosive engineering that have emerged since the AEC's 1966 study. A 2023 study by the US National Academies of Science, Engineering, and Medicine (NASEM) on the merits of different reactor and fuel cycle concepts made a similar recommendation regarding the utilization of HALEU (*9*). Given the large number of private corporations now counting on HALEU and the enormous sums flowing through the DOE to support a HALEU ecosystem, the DOE is not free of conflicts of interest. We therefore further recommend that the proposed study be peer reviewed by an independent body with the necessary technical expertise and security clearances. The NASEM or the JASON group (*14*) of technical consultants, having a history of credible work regarding weapons and proliferation, could conduct such a review and provide an unclassified summary for policymakers. The matter is urgent because industry needs to know sooner rather than later the true security risks to avoid designing reactors that could be sources of nuclear weapons material.

An Allied correspondent stands amid rubble and ruins in Hiroshima on 7 September 1945 after the dropping of an atomic bomb on 6 August.

A key outcome of this study should be to set a new, technically justified, and lower enrichment limit for weapons-usable uranium. According to the information available now, a reasonable balance of the risks and benefits would be struck if enrichments for power reactor fuels were restricted to <10 to 12% ^{235}U. If higher enrichments continue to be used, security-relevant quantities should be subject to appropriate physical protection. At present, the highest security classification of HALEU under both US and international standards is Category II, which has as a protection objective the early detection of theft. Security-relevant quantities of HALEU should be recategorized as Category I material, which requires the prevention of theft and is the standard used for analogous quantities of weapons-usable HEU and plutonium. A 10 to 12% threshold for Category I protection would allow many reactor designs to move forward with only modest economic consequences (*15*).

The decision on how to handle HALEU domestically has crucial downstream consequences for global security. Were HALEU to become a standard reactor fuel without appropriate restrictions determined by an interagency security review, other countries would be able to obtain, produce, and process weapons-usable HALEU with impunity, eliminating the sharp distinction between peaceful and nonpeaceful nuclear programs. Such countries would be only days away from a bomb, giving the international community no warning of forthcoming nuclear proliferation and virtually no opportunity to prevent it. An unfettered HALEU policy leaves no margin of safety. ■

REFERENCES AND NOTES

1. US AEC, "Research Reactors for Foreign Application: Report to the General Manager by the Director of Reactor Development" (1954); https://fissilematerials.org/library/haf54.pdf.
2. US NRC, "Rulemaking for Enhanced Security of Special Nuclear Material" (2015); https://www.nrc.gov/docs/ML1432/ML14321A007.pdf.
3. "Conversion of Research and Test Reactors to Low-Enriched Uranium (LEU) Fuel," Hearing before the Subcommittee on Energy Development and Applications and the Subcommittee on Energy Research and Production of the Committee on Science and Technology, US House of Representatives, 98th Congress (1984).
4. US AEC, Study of Strategic Importance of Nuclear Materials, (5 December 1966), as cited in "Report of the Advisory Panel on Safeguarding Special Nuclear Material" (1967); https://www.osti.gov/servlets/purl/4264753.
5. J. P. Lestone, M. D. Rosen, P. Adsley, *Nucl. Technol*. **207**, S352 (2021).
6. Web of Stories, "Meeting and working with Richard Feynman at Los Alamos," Interview with Hans Bethe (24 January 2008); https://www.webofstories.com/play/hans.bethe/92.
7. US DOE, "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-Grade Plutonium"; https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc29.html.
8. US DOE, "Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives" (Office of Arms Control and Nonproliferation, DOE/NN-0007, 1997); https://www.osti.gov/scitech/servlets/purl/425259.
9. NASEM, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors* (National Academy Press, 2023).
10. Nuclear Energy Institute to Secretary of Energy Rick Perry, "Need for High-Assay Low Enriched Uranium" (5 July 2018); https://www.nei.org/CorporateSite/media/filefolder/resources/letters-filings-comments/letter-perry-haleu-20180705.pdf.
11. US Congress, "Consolidated Appropriations Act, 2024," Public Law no. 118-42; https://www.congress.gov/bill/118th-congress/house-bill/4366/text.
12. UK Department for Energy Security and Net Zero, "UK invests in high-tech nuclear fuel to push Putin out of global energy market," (Press Release, 7 January 2024); https://www.gov.uk/government/news/uk-invests-in-high-tech-nuclear-fuel-to-push-putin-out-of-global-energy-market.
13. US NRC, "Fuel Cycle - Physical Security Requirements for Facilities With Category II Quantities of Special Nuclear Material Informational Sheet" (2023); https://www.nrc.gov/reactors/new-reactors/advanced/modernizing/rulemaking-and-guidance/fuel-cycle.html.
14. A. Finkbeiner, *Nature* **477**, 397 (2011).
15. A. W. Foss, C. Forsberg, "Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems" (Idaho National Laboratory, Report CON-21-64808-Revision-0, 2021); https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_54795.pdf.

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