SCIENCE & GLOBAL SECURITY
2016, VOL. 24, NO. 2, 131–137
http://dx.doi.org/10.1080/08929882.2016.1184533

Routledge
Taylor & Francis Group

RESEARCH NOTE

On the Origins and Significance of the Limit Demarcating Low-Enriched Uranium from Highly Enriched Uranium

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ABSTRACT
The International Atomic Energy Agency (IAEA) defines uranium with a ^{235}U isotope concentration of 20 percent as the threshold between low-enriched uranium (LEU) and highly enriched uranium (HEU), and as a significant waypoint on the path towards weapon-grade uranium (typically above 90 percent ^{235}U enrichment). The distinction between LEU and HEU is widely used in shaping nonproliferation policy, and it has featured prominently in commentary over Iran's nuclear program and the series of Nuclear Security Summits that since 2010 have sought to minimize civilian stockpiles and use of HEU. Yet the origin of this threshold is obscure, dating back 6 decades. This research note traces the political origin and the technical basis for this limit.

ARTICLE HISTORY
Received 7 April 2016
Accepted 12 April 2016

Background

In 1954, Lawrence R. Hafstad (1904–1993), director of reactor development at the United States Atomic Energy Commission, authored a memorandum aiming to set out the type and the maximum quantity of enriched uranium to be exported to support the operation of U.S. supplied research reactors keeping in view the amount and enrichment of uranium required to make a nuclear weapon (available in full at ipfmlibrary.org/haf54.pdf). This memorandum was in response to an August 1954 National Security Council policy directive: NSC 5431, *Cooperation with other nations in the peaceful uses of atomic energy*. The NSC directive, prepared with input from the Atomic Energy Commission (AEC), the Department of State, the Department of Defense, and the Central Intelligence Agency, followed from President Dwight D. Eisenhower's *Atoms for Peace* speech to the UN General Assembly on December 8, 1953.[1] Eisenhower's candid review of the perils of the nuclear arms race coupled with the offer to export nuclear technology and fissionable material, notably enriched uranium, for peaceful uses represented a sea change in American outlook. The preceding Truman administration had aimed at preserving the

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American monopoly in atomic weapons for as long as possible and failing that, to ensure the United States nuclear arsenal heavily outweighed any assembled by the Soviet Union.

Atoms for Peace was conceived in part as a propaganda exercise—at home to relieve the public dread associated with the military atom, and abroad in presenting a non-bellicose facet of U.S. nuclear policy. In his speech, Eisenhower proposed that "the governments principally involved, to the extent permitted by elementary prudence, should begin now and continue to make joint contributions from their stockpiles of normal uranium and fissionable materials to an international atomic energy agency."[2] He believed enriched-uranium donations to *Atoms for Peace* would not hamper the U.S. weapons program, whereas equivalent donations might constrain the build-up in the Soviet Union and other countries with smaller stockpiles of fissile materials and lesser capabilities to make them.

Finally, and perhaps most importantly, there was the potential commercial benefit to U.S. industry through the construction of nuclear power reactors. In the summer of 1954, there were no power reactors operating anywhere in the world, but it was understood that the acquisition and operation of research reactors would be a first step for a country launching a nuclear power program. The export of research reactors could establish U.S. vendors for future, more lucrative, commercial nuclear power reactor projects. These research reactor exports, under appropriate bilateral safeguards, were made possible by the passage of the 1954 Atomic Energy Act. This was accompanied by earmarking of a modest amount of fissionable material (enriched uranium) to fuel such reactors and by the introduction of reactor-training courses for foreign nationals. The Soviet Union was critical of the whole approach. Soviet officials pointed out that the widespread development of nuclear power reactors would in fact increase the amount of fissile material available for weapons and thus create a future proliferation problem. This objection was made directly by Foreign Minister Vyacheslav M. Molotov to Secretary of State Dulles at a disarmament conference in Geneva in May 1954[3] and reiterated, for example, during discussions over the founding of the IAEA.[4]

NSC 5431 recommended supporting construction of research reactors abroad and the provision of fuel in the requisite amounts. It specified, however, that the fissionable material to fuel these reactors should be "of less than weapons grade." Hafstad's memorandum points out that "there has been no official determination as to what range of U enrichment constitutes weapon quality" and proceeds to offer a basis for determining what the uranium enrichment criteria and material amounts should be for research reactor fuel exports. Hafstad observed:

> The minimum enrichment which is capable of supporting a nuclear explosion with an infinite mass of material has been estimated as about 5%. Information from Los Alamos indicates that 10 percent enriched uranium is not suitable for any practical weapon but no definite upper limit can be set. For higher concentrations it would be possible to prevent assembly of a weapon by restricting the total amount of material issued of any given assay. For example, an approximate expression to show the amount of material of various assays required to produce a weapon of 1 kT yield of the type requiring minimum amounts of

material is $2/C^{1.7}$ = kg of total U, where C is the fraction of U-235. Use of this formula shows 31 kg for 20 percent assay and 2 kg for fully enriched uranium. This formula is of limited usefulness for low assays and it is considered that 10 percent assay is safe in any quantity.

The memorandum recommends the following criteria:

(a) That enriched uranium of assay up to 10 percent U^{235} be regarded as not of weapons quality in any amount.
(b) That enriched uranium of assay between 10 percent and 20 percent U^{235} be regarded as not of weapons significance provided the total quantity held by any one country does not exceed that given by the formula, kg total U = $2/C^{1.7}$. Although in theory the maximum quantity of material permitted by this formula might allow the fabrication of a single weapon of 1 kt yield this would require the utmost ingenuity.

Three significant points from this memo are particularly relevant for assessing the subsequent development of U.S. policy towards exports of enriched uranium for research reactors.

1. Weapon usability and enrichment level of uranium for foreign research reactors

In 1954, fifteen research reactors were operating in the United States and many additional ones were under construction. It was clearly understood that their weapon-grade highly enriched uranium fuel (93 percent ^{235}U) would not be made available for export.

The Hafstad memorandum refers to information from Los Alamos to identify an enrichment level of 10 percent ^{235}U as “not suitable for any practical weapon,” and as “safe in any quantity.” The document notes that using 20 percent enriched material for a weapon would “require the utmost ingenuity” and identifies this enrichment level as a tradeoff between research reactor performance and weapon-usability. The proposed use of 20 percent enriched fuel for research reactor exports would require only about a 20–25 percent increase in uranium-235 loading compared to the fuel used in U.S. reactors and “should not result in large sacrifice in cost or usefulness.” It would appear the 20% limit was chosen to limit the negative impact on reactor performance and cost, and the proliferation risk created by choosing 20 percent enriched uranium as fuel was balanced by an additional constraint on the amount of such material to be made available to foreign countries.[5]

It is worth noting that this analysis is not entirely consistent with the definitions later adopted by the International Atomic Energy Agency, which considers uranium enriched up to 20 percent ^{235}U as “indirect use material” that cannot be used for “the manufacture of nuclear explosive devices without transmutation or further enrichment.”

2. Explosive yield and minimum amount of material needed

The memorandum considers the ability to achieve a yield of 1 kt, i.e., one kiloton TNT equivalent, as a threshold value for a nuclear weapons capability and offers a simple formula for establishing the “minimum amounts of material” for a weapon able to produce such yield.

$$M(\epsilon) = \left(\frac{2}{\epsilon^{1.7}}\right) \text{kg}, \tag{1}$$

It notes material between 10 percent and 20 percent enrichment is “not of weapons significance provided the total quantity held by any one country does not exceed that given by the formula.” From Hafstad’s expression $M(\varepsilon)$, the amount (M) of material with enrichment ϵ needed for a 1-kt explosion is as low as 2.3 kg for weapon-grade highly enriched uranium (93 percent U-235). Remarkably, the formula suggests about 31 kg of 20 percent enriched uranium are sufficient for a nuclear device with a 1-kt yield (see Figure 1).

Again, these reference values can be compared to those that have been adopted by the International Atomic Energy Agency: A significant quantity is defined as “the approximate amount of nuclear material [including unavoidable losses due to conversion and manufacturing processes] for which the possibility of manufacturing a nuclear explosive device cannot be excluded.” For uranium, a significant quantity is defined as 25 kg of U-235 in highly enriched uranium, i.e., about 4–12 times higher than the values used here.

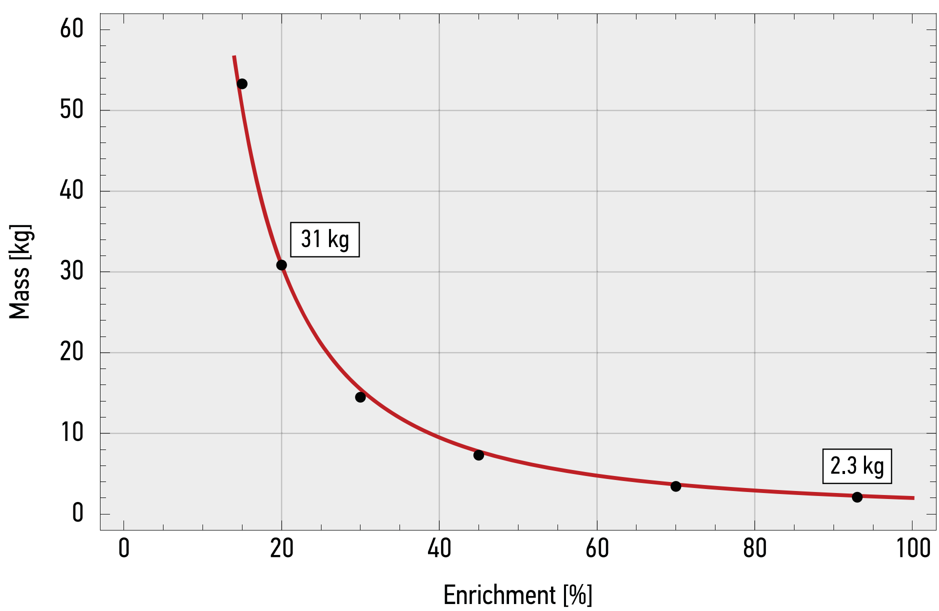

Figure 1. Minimum amount of uranium needed for an explosive yield of 1 kt(TNT) for a nuclear weapon of the “type requiring minimum amounts of material.” The line shows the amount as determined by the expression from the 1954 Hafstad memorandum. The dots show scaled (“fractional”) critical masses for bare metallic uranium calculated with Monte Carlo simulations. This minimum amount is equivalent to about 4% of a bare critical mass. Note that the efficiency of such a device would be very low; for example, in the case of fully enriched uranium, the efficiency is only on the order of 3% compared to almost 20% for the (plutonium-based) Nagasaki bomb.

As for the 1-kt yield criteria adopted by Hafstad, for comparison, the first nuclear weapons tested and used had yields on the order of 15–20 kt. By 1952, the yield of pure fission devices had increased to 500 kt, and thermonuclear weapons allowed yields in the megaton range. A yield of 1 kiloton is still much larger than the yields of the largest conventional bombs, which are on the order of 10 tons of TNT. The blast yield of the 1995 Oklahoma City bomb was about 2 tons TNT equivalent.

3. Available amount of uranium for foreign research reactors

In addition to the enrichment level, Hafstad's analysis emphasizes the importance of limiting the maximum amount of uranium that would be supplied such that "the total quantity held by any one country" does not exceed a threshold quantity. It also recommends an initial allocation of a total of 100 kilograms of U-235 enriched to 20 percent or less, and suggests that this would be sufficient to support "three to perhaps fifty" research reactors abroad.

The underlying assumptions for this assessment turned out to be unrealistic, however. Most importantly, Hafstad's analysis assumes that most clients would be interested in very low-power reactors or other research facilities, including subcritical experiments and zero-power critical assemblies, and that "most of the material probably could be distributed at an assay of 10 percent U-235 or less if necessary." Instead, the maximum enrichment of 20 percent quickly became the preferred option for many customers, in part because U.S. vendors sold several so-called "MTR-type" reactors abroad. These reactors were based on the original Material Testing Reactor, which operated at a power level of 30 MW (thermal) with weapon-grade HEU at what is now the site of the Idaho National Laboratory. Several early U.S. supplied MTR-type reactors were operated at 5 MW thermal, and a typical in-core uranium inventory for these reactors is 20–30 kg when enriched to 20%.[6] Clearly, even a single reactor of this type challenges the 31-kg limit proposed in the memorandum, especially once refueling is required and spent fuel is discharged and stored onsite. Foreign countries with ambitious nuclear programs and with more than one research facility under construction early on, such as Germany or Japan, would therefore quickly exceed the proposed mass limit.

In 1958, the principle of limiting uranium enrichment for foreign customers to 20 percent was abandoned altogether, and the United States began exporting weapon-grade highly enriched uranium instead. At that point, trying to apply Hafstad's formula to determine a maximum amount of HEU research reactor fuel to export became meaningless, as it would have limited such exports to about 2 kg of weapon-grade uranium per country—not enough to operate any research reactor in the megawatt-range. Without these restrictions, HEU quickly became the standard fuel for U.S. supplied research reactors, and most existing reactors were converted from LEU to HEU fuel. The amounts of exported U.S. HEU ramped up quickly and reached almost 2.7 tons in 1967 alone (see Figure 2). By 1978, the United States had already exported almost 18 tons of HEU for use as research reactor fuel.

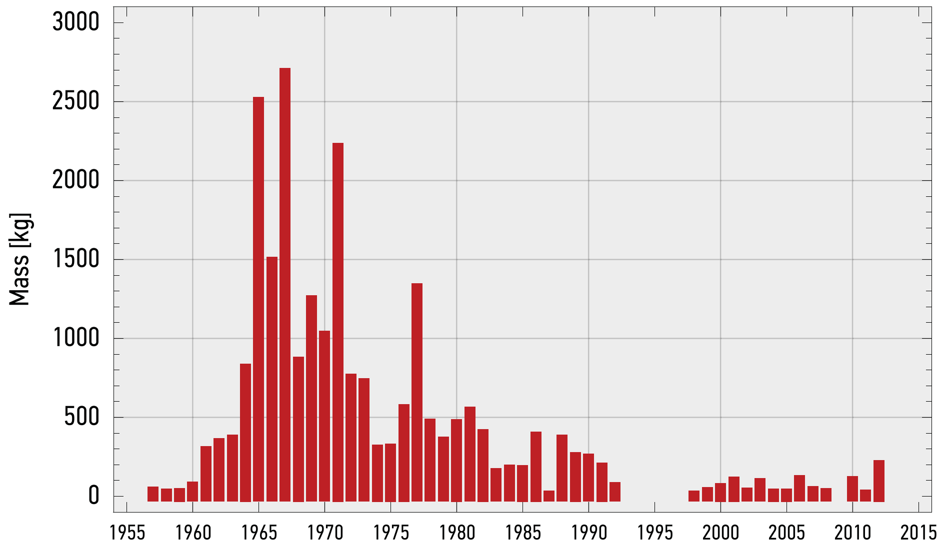

Figure 2. Exports of U.S. HEU used for targets in nuclear research or test reactors. Once authorized, annual exports rose quickly and reached almost 2700 kg in 1967. Source: *Report to Congress on the Current Disposition of Highly Enriched Uranium Exports Used as Fuel or Targets in Nuclear Research or Test Reactors*, Nuclear Regulatory Commission, January 2014.

Growing proliferation concerns in the late 1970s eventually led to the establishment in 1978 of the U.S. Reduced Enrichment for Research and Test Reactors (RERTR) Program.[7] The aim of the program was to develop new low-enriched uranium fuels that would allow an end to the use of HEU in civilian research reactors, especially in non-weapon states. There was however no consideration of Hafstad's original proposal of limiting the amounts of up to 20 percent enriched uranium to be made available to any country. International efforts to limit and end civilian use of HEU have further intensified since the 2000s, especially with the establishment of the Global Threat Reduction Initiative (GTRI) in 2004.[8] It is currently planned to completely phase-out the civilian use of HEU by the year 2035 globally.[9] A country is considered cleaned-out of HEU once it has less than one kilogram of HEU. In 2016, the United States announced plans to also examine the viability of using low-enriched uranium to fuel naval reactors.[10]

Summary

This research note traces the origins and the significance of the 20 percent threshold that demarcates low-enriched uranium (LEU) from highly enriched uranium (HEU). The original analysis from 1954 presented by the director of reactor development at the U.S. Atomic Energy Commission proceeds in several steps, but follows a simple principle: no foreign country ought to receive enough material to make one nuclear explosive device with a yield of one kiloton TNT equivalent. Using this criterion, an enrichment of 10 percent was considered "safe in any quantity." In contrast, making a nuclear weapon using 20 percent enriched uranium would "require the utmost ingenuity," but the minimum amount needed is only on the order of 30 kg (compared to 2.3 kg for weapon-grade HEU). The memorandum went on to recommend exporting enriched uranium up to an enrichment level of 20 percent such that the total amount held by a foreign country does not exceed 31 kg. While the enrichment limit remains a key element in nonproliferation policy today, the mass limit was quickly abandoned and later forgotten.

Notes and references

1. Address by Mr. Dwight D. Eisenhower, President of the United States of America, to the 470th Plenary Meeting of the United Nations General Assembly, New York, 8 December 1953, www.iaea.org/about/history/atoms-for-peace-speech.
2. *Ibid.*
3. John Krige, "Atoms for Peace, Scientific Internationalism and Scientific Intelligence," *Osiris*, 21 (2006): 16–222.
4. Soviet Aide-Memoire on the International Atomic Energy Agency, October 1, 1955. RG326 (A1 Entry 76, Formation of the IAEA, 1954–1957, Box 2), National Archives at College Park.
5. Consistent with this finding, at the 1955 Atoms for Peace conference, Alvin Weinberg reported that he had "just received information from my country that sample UO2-aluminum 20 per cent enriched fuel elements of the type which will be available to foreign countries have now been tested both in the LITR and in the MTR" (Session 9A, Vol. II, August 12, 1955, 430).
6. Early examples for U.S. supplied MTR-type research reactors include the IAE-R1 in Brazil (5 MW, first criticality in 1957), the FRM-I in Germany (4 MW, 1957), the DR-2 in Denmark (5 MW, 1958), and the FRG-I in Germany (5 MW, 1958). For a comparison of different MTR-design options, see for example "Benchmark Calculations for MTR type Reactors with High, Medium, and Low Enrichment," Appendix F-5 in Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels Guidebook, IAEA-TECDOC-233, International Atomic Energy Agency, Vienna, August 1980.
7. In parallel, the International Nuclear Fuel Cycle Evaluation (INFCE) led by the IAEA also acknowledged these proliferation risks. The final report noted: "The trade in and widespread use of highly enriched uranium and the production of fissile materials constitute proliferation risks with which INFCE is concerned." With regard to research reactor fuel, the study recommends "enrichment reduction preferably to 20% or less which is internationally recognized to be a fully adequate isotopic barrier to weapons usability of 235U" (*Advanced Fuel Cycle and Reactor Concepts*, Report of the INFCE Working Group 8, 1980, International Atomic Energy Agency, Vienna, 43).
8. The U.S. program is now called Material Management and Minimization (M^3).
9. For a recent review and assessment of these efforts, see National Academies of Sciences, *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors* (Washington, DC: National Academies Press, 2016).
10. *Feasibility of Low Enriched Uranium Fuel in Naval Reactor Plants*, Fact Sheet, The White House, Office of the Press Secretary, March 31, 2016, www.whitehouse.gov/the-press-office/2016/03/31/fact-sheet-feasibility-low-enriched-uranium-fuel-naval-reactor-plants.