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Highly enriched uranium and crude nuclear weapons

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English summary

Nuclear weapons can be constructed with either highly enriched uranium or plutonium. The uranium weapons are less technically demanding and do not require testing. Developing states pursuing a secret weapons programme, and terrorist organisations seeking nuclear capabilities will most likely choose a uranium weapon.

The amount of uranium needed to construct one weapon is dependent on the enrichment level of the material. We show that if the enrichment exceeds 80 % in uranium-235, even a crude design could work with less than 80 kg.

Sammendrag

Kjernefysiske våpen kan lages med enten høyanriket uran eller plutonium. Uranvåpnene er mindre teknisk krevende og det er mindre behov for prøvesprengning. Uran vil sannsynligvis være førstevalget til en terrororganisasjon eller en mindre utviklet stat som starter et hemmelig program.

Mengden uran som behøves for å lage ett våpen avhenger av anrikningsgraden til materialet. Vi ser at hvis andelen uran-235 overstiger 80 %, kan selv et primitivt våpen lages med mindre enn 80 kg.

Contents

1 Introduction

Highly enriched uranium (HEU) in the civilian nuclear sector is considered a proliferation risk. In this work we have tried to obtain a feel for what would be needed technically if a non-state actor was to construct an improvised nuclear device. We have also calculated the critical masses for uranium in different enrichments, using commercially available software.

2 Highly enriched uranium

2.1 What is HEU?

Fission is the process whereby a large atomic nucleus splits into two comparatively equal pieces, releasing energy and typically two or three neutrons. The released neutrons can trigger fission in nearby atoms. When the released neutrons from one fission on average induce at least one new fission, the process is self-sustaining, known as a *chain reaction*. The minimum mass required to sustain a chain reaction is known as *critical mass*. If the assembled mass is greater than one critical mass (the mass is *supercritical*), the chain reaction grows in intensity, and a *nuclear explosion* occurs, as illustrated in Figure 2.1.

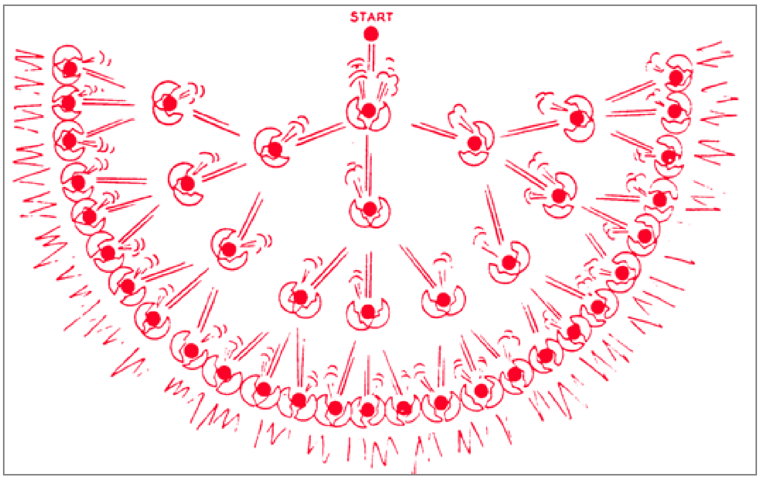

Figure 2.1 A simple representation of an explosive chain reaction.

Natural uranium consists of 0.72 % uranium-235 (U-235) and 99.27 % uranium-238 (U-238), as well as a minute fraction of uranium-234 (U-234). U-235 can undergo fission induced by neutrons of all energies (it is a *fissile* isotope), while U-238 only fissions when reacting with *fast neutrons*[1] (it is a *fissionable* isotope). Neutrons resulting from fission will have a range of energies, and only a few of the neutrons qualify as fast. Therefore, in order for a uranium assembly to be capable of undergoing a nuclear chain reaction, the uranium must be sufficiently

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[1] Fast neutrons are neutrons of high energies.

enriched in U-235. This means that the fraction of U-235 must be increased relative to the natural isotope composition.

Different uses of uranium require different degrees of enrichment. *Natural uranium* may be used in reactors *moderated*[2] by heavy water or graphite. *Low-enriched uranium* (LEU) is enriched uranium in which the fraction of U-235 is less than 20 %. Most nuclear power plants use uranium fuel enriched to about 3-5 %. This material cannot be used for nuclear explosives. *Depleted uranium* (DU) is a waste product from the enrichment process. It typically contains 0.2-0.5 % U-235.

HEU is defined as uranium enriched to a minimum of 20 % U-235. HEU is used mostly for military applications; nuclear weapons and the propulsion of submarines. Civilian uses of HEU include power generation, propulsion of ice breakers, fuel for research reactors and production of radioisotopes in such reactors. At 90 % or more U-235 the uranium is said to be of *weapons quality,* but HEU of somewhat lower enrichment could be used for a less optimal weapon.

2.2 How to obtain HEU

In the *enrichment* process, the fraction of U-235 is increased from the original 0.72 % to whatever the application in question requires. Several enrichment methods exist; generally they utilise the small mass difference between U-235 and U-238 and require large facilities with sophisticated and expensive equipment. Enrichment is considered to be the most demanding step in the production of nuclear weapons, and to be beyond the technical capabilities of non-state actors.

The easiest way for a non-state actor to obtain HEU would be to intercept civilian HEU at some point in the transfer from the enrichment plant via fuel fabrication to placement in a research reactor, or when the spent fuel has been removed from the reactor core. When uranium fuel is burned in a reactor, only part of the uranium undergoes fission. For HEU fuel, even the spent fuel that is eventually removed from the reactor will contain a relatively large fraction of U-235. This means it is possible to recover the remaining uranium still as HEU from the spent fuel by *reprocessing*[3] it. Most spent nuclear fuel is highly radioactive, making it difficult to extract the remaining uranium in a safe manner. However, many civilian facilities have in preliminary storage spent fuel assemblies that are old or only lightly irradiated (and therefore significantly less radioactive), thereby making them vulnerable to theft or diversion. We can also speculate that personal safety is not the highest priority for a terrorist group willing to use nuclear weapons.

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[2] Moderators are materials that slow down neutrons, increasing the probability of neutron capture in U-238. This in turn generates plutonium-239 (Pu-239), which is fissile. In addition, U-235 fissions more readily with slower neutrons. These two processes together greatly reduce the need for U-235 in the fuel. Regular water is commonly used as moderator in reactors, but it is not effective for natural uranium. Heavy water or graphite is used in this special case because of their good moderating qualities combined with their property of absorbing very few of the neutrons.

[3] Reprocessing is the chemical separation of uranium or plutonium from the fission products in the spent fuel. The procedure does not discriminate between the different isotopes, giving the same enrichment level in the product as in the fuel elements.

Enrichment methods

There are several methods available for the separation of U-235 from U-238. These include;

- gas centrifuge;
- gaseous diffusion;
- electromagnetic isotope separation (EMIS);
- chemical exchange;
- ion exchange;
- jet nozzle;
- atomic vapour laser isotope separation (AVLIS);
- and molecular laser isotope separation (MLIS).

All of the above-mentioned methods require industrial scale plants and supporting infrastructure to produce enough material for a bomb inside a few years.

In Europe, the consortium supplying most of the civilian fuel (Urenco) has chosen centrifuge enrichment, while the United States only recently has switched focus from gaseous diffusion to centrifuges. The other methods have not been utilized on a large scale.

A small section of the Ohio centrifuge enrichment plant. A centrifuge is typically two to four meters tall. (Picture courtesy of U.S. Department of Energy.)

Many of the world's research reactors are located on university campuses, with a minimum of security compared to commercial power reactors and of course nowhere near the security surrounding military HEU. The amount of U-235 in such a reactor at any one time is not nearly enough for a viable weapon: Most reactors of this type operate on less than 3 kg U-235, the larger approaching 10 kg [1]. Compared to the critical masses we present in Section 3.5, we see that this amount would need a very sophisticated design indeed to give any nuclear yield. But when combining this uranium with stored spent fuel, there is no question that enough material could be acquired.

3 Improvised nuclear devices

An *improvised nuclear device* (IND) can be defined as a device giving some nuclear *yield*, without being made to military specifications. The definition covers concepts from dropping two pieces of fissile material onto each other, to fairly advanced weapons constructions. The discussion below illustrates the different levels of complexity.

3.1 Primitive state actors

The *Treaty on the Non-Proliferation of Nuclear Weapons (NPT)* divides the world into nuclear weapons states and non-nuclear weapons states. The five states that had tested nuclear weapons before 1 January 1967, constitute the recognized nuclear weapons states, while all other signatories are required not to develop such weapons. If a state nevertheless decides to pursue a hidden weapons program, the testing of a weapon would give the game away. Thus, straightforward, proven designs would be preferable. A state with limited resources; infrastructure, materials, or know-how, would by necessity go for a simple design. An example of this is the secret programme in South Africa, which focused on a straightforward gun-type weapon [2-4]. Nevertheless, a state would want predictability in performance, and including weapons intended for a military programme in the concept of improvised nuclear devices may be extending the definition too far.

3.2 Non-state actors

For terrorist groups, the development of a nuclear weapon would be a different process. Some materials and components easily acquired by a state could be difficult to obtain for private companies. It would be advantageous to limit the time spent in preparation, in order to minimize the threat of discovery by police or intelligence agencies. Such a group may be willing to renounce to some extent on the precision and predictability of the performance and focus on just producing an undeniably nuclear effect.

State sponsored terrorist groups normally have more freedom of operation, not having to conceal all their activities. This said, very few states, if any, would risk being linked to an attack with weapons of mass destruction, especially nuclear weapons. We see the possibility of a state abetting, or even silently accepting, the construction of a nuclear device by a non-state actor as very remote. Thus, such a group would want to carry out its pursuit hidden also from any state which normally supports them.

3.3 Types of improvised nuclear devices

All nuclear weapons require a fissile material such as HEU or plutonium. Due to its relatively low background of spontaneous fission neutrons, HEU is generally considered much more suitable than plutonium for use in an IND [3;5;6]. The low spontaneous fission rate facilitates the IND design by the fact that the probability of a *predetonation*[4] is relatively low. This allows for

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[4] Predetonation is when the chain reaction begins at a too early stage, before the optimal configuration is reached, thus giving an unpredictable but low nuclear yield.

the use of a gun-type IND; a slower joining mechanism which, however, is far easier to design and build than an implosion type device (compare Figure 3.1 with Figure 3.2). The latter requires for example high quality explosive lenses (made of conventional high explosives), more sophisticated detonation equipment, and generally more high precision machining of its parts.

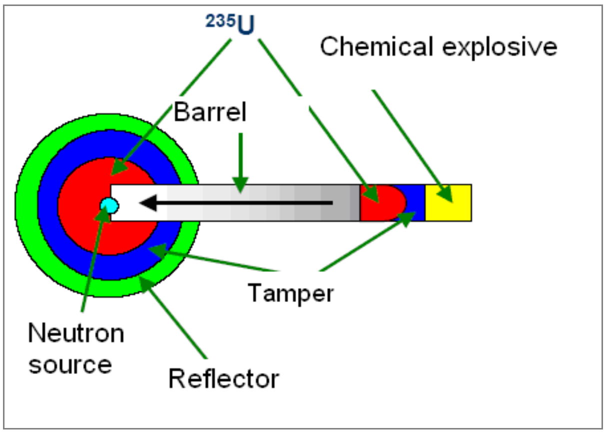

Figure 3.1 Design principle for a gun-type weapon. A subcritical piece of fissile material is fired into a stationary subcritical piece, resulting in a supercritical assembly without any change in density.

An additional point in favour of HEU over plutonium in crude weapons production is the difference in radioactivity levels. Reactor plutonium[5] is highly radioactive, generating heat and a hazardous radiation field for handlers, as well as emanating easily detectable radiation. HEU is only slightly radioactive, and such problems are minimized.

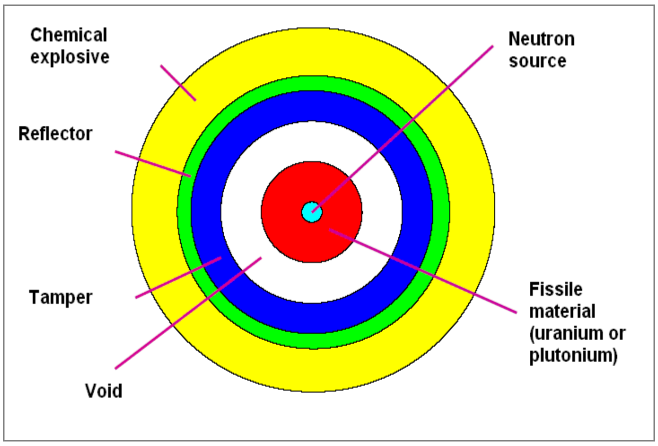

Figure 3.2 Design principle for an implosion type device. A near critical mass is compressed by conventional explosives and becomes supercritical by the increase in density.

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[5] Reactor plutonium is commonly defined as containing over 18 % Pu-240, while plutonium with less than 7 % Pu-240 is denoted weapons plutonium [7]. Any composition of plutonium isotopes could in principle be used as weapons material [8;9].

Radiation and heat properties of plutonium

- *Radiation dose* is measured in the unit sievert (Sv), or more conveniently a thousandth of a Sv; millisievert (mSv). At the surface of a few kg of the metal, typical reactor plutonium gives an external gamma dose of 150 mSv/h, weapon grade plutonium gives 9.4 mSv/h, and weapons grade HEU gives 0.015 mSv/h [5]. By comparison 3-5 Sv is lethal dose for half of the people exposed [10] , and 20 mSv/year is the international recommendation for radiation workers [11].

- The heat generated is 10-14 W/kg for reactor plutonium, 2-2.5 W/kg for weapons grade plutonium, and 0.00026 W/kg for weapons grade HEU [5;12].

HEU appears in different forms, including uranium hexafluoride gas (UF_6), uranium oxides, and uranium metal. Making uranium-based INDs requires casting of highly enriched uranium metal into suitable shapes. For that reason, the most attractive form of HEU for the purpose of nuclear terrorism is metallic HEU. As uranium metal powder ignites spontaneously in air, mechanical processing is no trivial matter. Other forms of HEU would necessitate chemical processing in order to convert the material into uranium metal. Crystalline uranium oxide powder could conceivably be used directly, but the mass and volume required to reach critical mass in a gun-assembly would be many times that of metal, because of the lower density of the material as well as the oxygen increasing the distance between the uranium atoms [9].

There is no argument that once the fissile material is acquired, HEU is far easier to use. Some argue, however, that plutonium is easier to obtain than HEU, as most of the worlds HEU is military, while plutonium is an unavoidable by-product in power reactors. This would suggest that the difficulties inherent in the implosion design are worth overcoming [3;6;13]. More HEU will be moved to the civilian domain, however, with the further dismantlement of nuclear weapons, as has been done under bilateral agreements between the Unites States and Russia.

3.4 What is needed to construct an improvised nuclear device?

The most important component of any nuclear device is of course the fissile material. How to obtain this has been covered in Section 2.2. If this most difficult step is achieved, there is still a complex construction task ahead. One could picture the simple approach of joining two naked, subcritical pieces of HEU, but this would require a suicide mission and also probably result in a very low yield. More likely, there would be an attempt to construct a device that can be made to go off under more controlled conditions.

A crude weapon will require at least some sort of joining mechanism, driven by explosives, to prevent a *fizzle*[6]. A *tamper* to keep the explosion together for an increased fission yield and a *reflector* for keeping more neutrons in the fissioning volume will increase the effect.[7] A neutron source can trigger the fission at exactly the right moment. Figure 3.1 shows the design principle.

Little Boy (Figure 3.3), the nuclear bomb detonated over Hiroshima, was a simple gun-type device. The length was 3 m and the diameter 70 cm. The total weight was 4,400 kg [14]. It is reasonable to assume that a terrorist group, aiming to construct an HEU-based IND, would pursue a design somewhat similar to, or equally crude as, this first nuclear weapon. By using modern high explosives and reducing the surrounding structure to a minimum, this design could be made small enough to fit into a van [3]. Even though the fundamentals of its construction are in the public domain, this bomb would presumably still be demanding for a non-state actor to reproduce properly. All the different engineering tasks involved in such a project call for a group of people skilled in high explosives, electronics, and mechanical machining, and in addition the group would need an understanding of neutronic and radiation properties.

The yield of Little Boy was about 13 *kt*[8] [3;15]. Note that even a not very "successful" IND may lead to very serious consequences. Just 1 % of 13 kt would constitute an enormous explosion, and the psychological effect of a first terrorist attack proven to be nuclear would be enormous no matter what the actual yield.

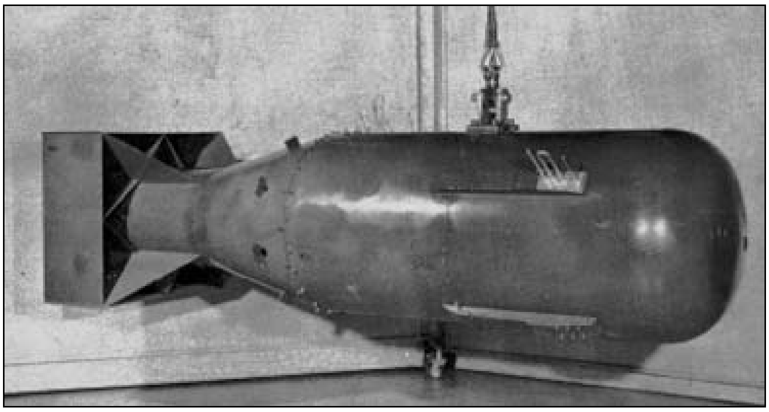

Figure 3.3 Mock-up of the casing of the Hiroshima bomb, Little boy. (Photograph courtesy of U.S. Department of Energy.)

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[6] When the yield of a nuclear detonation is less than expected, the term fizzle is used.

[7] The tamper and the reflector may be the same or two different materials. Often mentioned materials are beryllium, tungsten, and natural or depleted uranium.

[8] The unit for nuclear explosion yield is given as tonnes equivalent of TNT. That is; a one kilotonne nuclear weapon would give the same explosive energy as one thousand metric tonnes of TNT. The abbreviation for kilotonne is kt. Weapons yielding more than a million tonnes TNT (a megatonne or Mt) have been constructed.

3.5 How much HEU is needed in an improvised nuclear device?

A common statement in the literature is that to produce a modern implosion type nuclear weapon, 10-15 kg of weapons grade HEU is needed [3;5;16]. A modern gun-type weapon with a neutron reflector may require 25 kg HEU [5;9]. For a crude gun-type weapon, more than twice this mass is required [3;5;15;17]. Little boy used approximately 60 kg uranium, on average enriched to 80 % [3;14], and the South African weapons about 55 kg 90 % HEU [3;4].

As stated in Section 2.1, at least one neutron from each fission process must induce a new fission to sustain a nuclear chain reaction. This is achieved with exactly one critical mass. So what is the difference in critical mass for LEU compared to HEU? From Figure 3.4 we see that there is a dramatic decrease in the critical mass, when going from LEU to higher enrichments. Table 3.1 summarizes the values, dropping from almost four tonnes, corresponding to a radius of 36.5 cm, for 10 % enrichment, to 47 kg and 8.5 cm for 100 % U-235. Figure 3.5 shows an example of how the critical mass decreases several times when a thick layer of an efficient reflector is added to the uranium sphere, compared to the naked sphere. All these calculations give the minimum required material for a chain reaction to occur; to create an explosive effect would call for larger masses.

4 Summary

A gun-type weapon with uranium as the fissile material is by far the easiest nuclear weapon to construct with limited resources. This design principle is simple and reliable and does not require a nuclear test. We see that HEU at 80 % or more enrichment has a critical mass of less than 100 kg. If a neutron reflector could be added, this mass would be significantly lower, and even less enriched uranium could be serviceable in a weapon. The fact that reactor plutonium in many cases may be easier to obtain, does not suggest that HEU is no longer an attractive material for INDs.

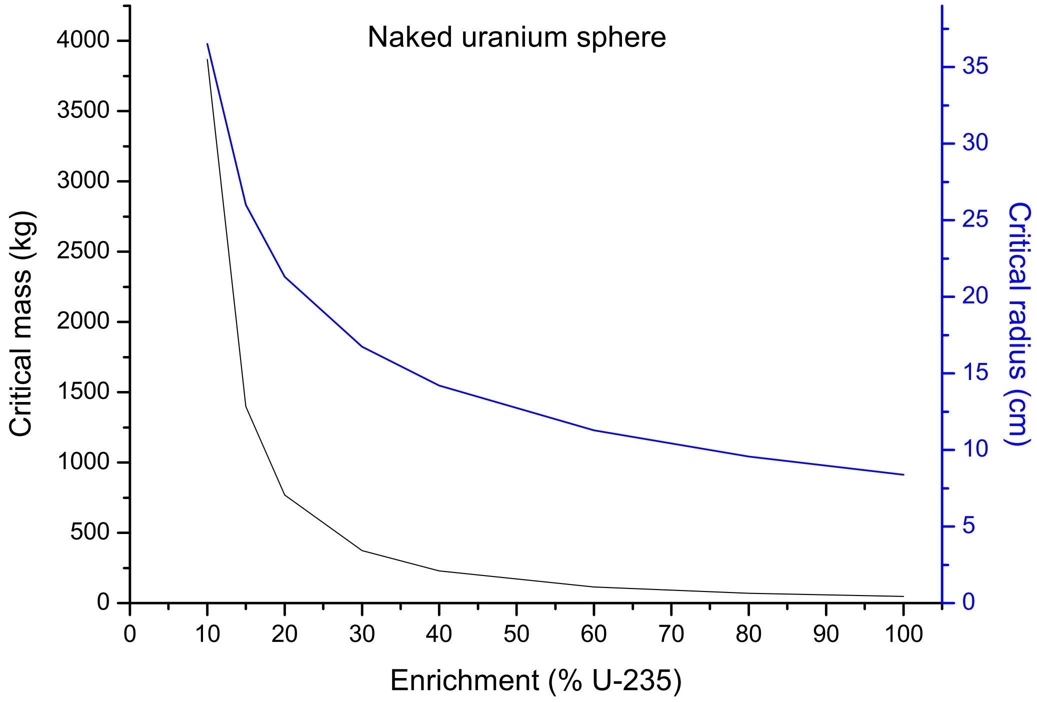
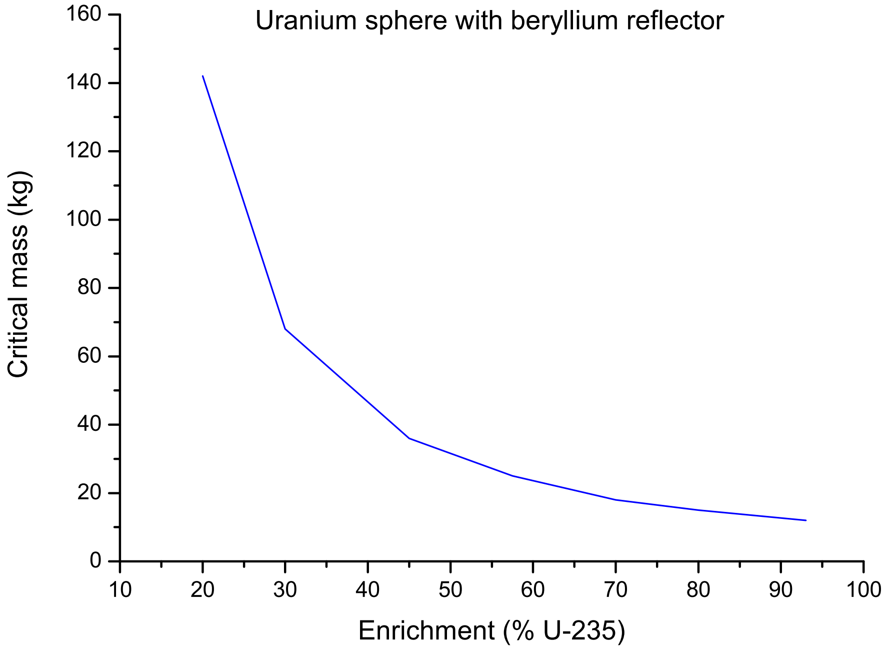


Figure 3.4 *The black line represents critical mass for a naked uranium sphere at different degrees of enrichment, while the blue line shows the corresponding radius of the sphere. The calculations were performed with MCNPX 2.4.0.*

Enrichment (% U-235)	**Mass (kg)**	**Radius (cm)**
10	3870	36.5
15	1399	26
20	769	21
30	373	16.5
40	228	14
60	114	11
80	70	9.5
100	47	8.5

Table 3.1 Critical mass and critical radius for a naked uranium sphere. The calculations were performed with MCNPX 2.4.0.



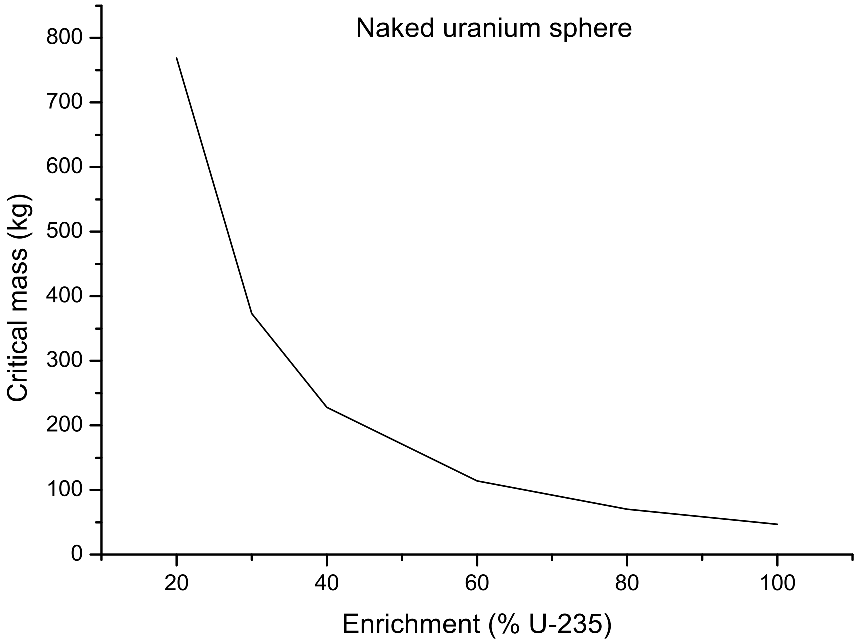


Figure 3.5 *The blue graph shows the critical mass for a uranium sphere surrounded by 15 cm of beryllium as a function of the enrichment level. The black graph shows the corresponding masses for a naked uranium sphere, the same as in figure 3.4. Note the different scales. The calculations were performed with MCNPX 2.4.0.*

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