Compressibility of Uranium and the Minimum Quantity for a Fission Weapon

Ara Barsamian
Nuclear Non-Proliferation Institute; Morris Plains, NJ 07950 USA
www.nuclearnonproliferation.org

Introduction

In order to answer the question of what is the minimum amount that Iran or any proliferant needs for a fission explosive (Highly Enriched Uranium or Plutonium), we need to examine the compressibility of these metals by explosive driven implosions. The frequently quoted IAEA “Significant Quantity” (SQ) numbers of 8 kg Pu and 25 kg U235 are misleading, and dangerous to rely upon for policy decisions.

It was known since 1943 that critical mass varies roughly with the square of the density of fissile materials, and one of the efforts during Manhattan project was to economize the scarce Plutonium needed for Fat Man- type bombs by using implosion to roughly double the density of Plutonium.

Soviet scientists, particularly A’ltshuler and Zababakhin [1] refined the art of implosion by recognizing that isentropic compression could produce much higher densities than the straight shock driven implosion, and they developed the technology used in their nuclear weapons program in late 40’s - early 50’s, using multilayered graded impactors. This technique was refined in the US in the mid 50’s and early 60’s, making possible density increase by a factor of three, thus doubling yields, or the converse, using less fissile material in so called “fractional crit” weapons.

In the case of Iran, using 93% HEU metal bare sphere with M_c of 52kg, isentropic compression by a factor of 3 decreases the critical mass by a factor of approximately 9 to about 5.8kg, and for delta phase Plutonium metal sphere, from M_c of about 16kg to about 1.8kg. To get a yield, you need a super critical mass, so add another 10%, for a total of 6.5 kg HEU and 2 kg Pu respectively.

Discussion

Typical shockwaves both compress and heat the material, limiting the amount of compression that can be obtained with normal flying plate explosive experiments to about 2 for a pressure of about 6 Mbars in Uranium. Figure 1 shows the shock Hugoniot equations of state (EOS) obtained initially with explosive flyer impactors (invented by Goranson in US and A’ltshuler in the USSR around 1948), and later with more sophisticated spherical shock amplifiers [2]. To obtain higher pressures, A’ltshuler and Zababakhin devised hemispherical implosion devices to increase pressures by an order of magnitude, initially combining the flying impactor concept with the amplification through convergence offered by spherical implosion.

The Soviet scientists developed multistage cumulative spherical explosive devices [3] that could provide impactor speeds of about 18 km/s and pressures of 1.35TPa (about 13.5 Mbars), and a compression factor (σ) of about 2.5 (see Fig. 2) .

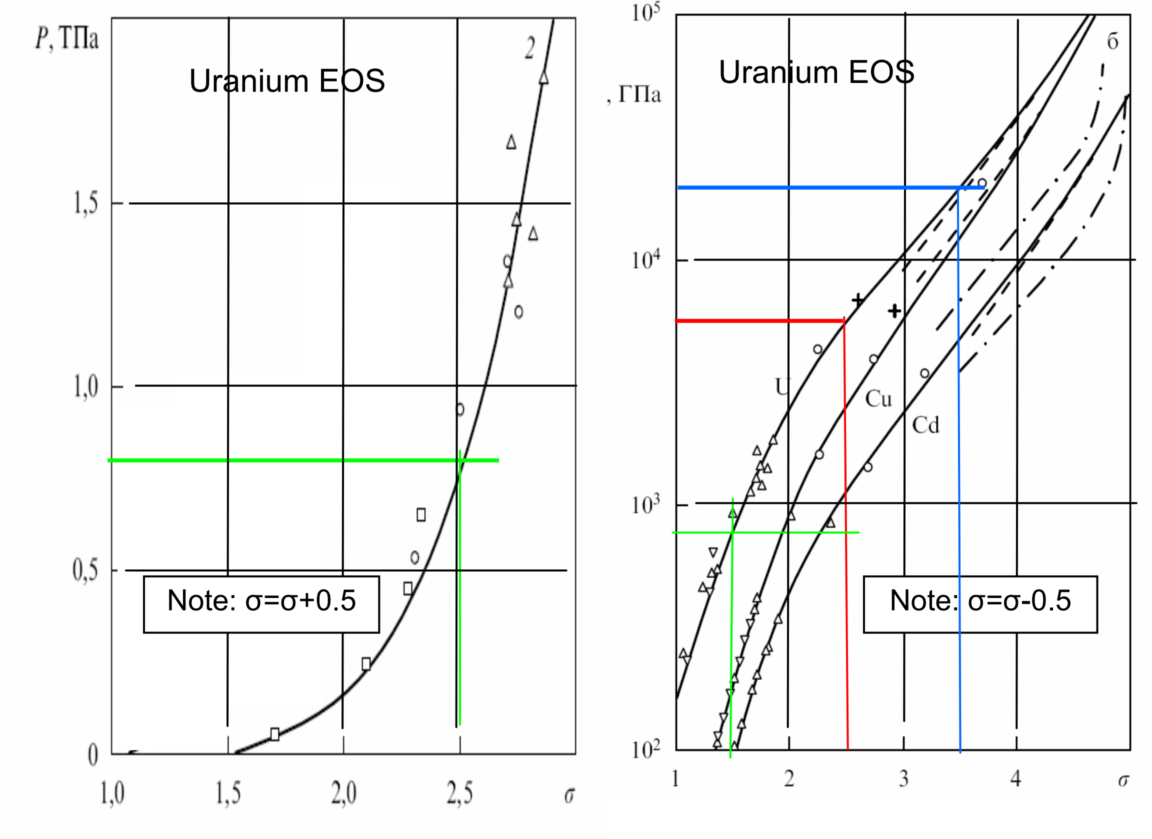

Fig. 1 The shock Hugoniot EOS for Uranium (reference 2)

Zababakhin through his work on cumulation of energy developed in 1948 the idea of multicascade explosive plate acceleration, and applied it to “cascading” the hemispherical explosive stages. The spacing gaps between cascades also provided a primitive quasi-isentropic compression of the metal plates, and this led to a more thorough analysis of isentropic compression of fissionable materials [3], and the means to achieve it.

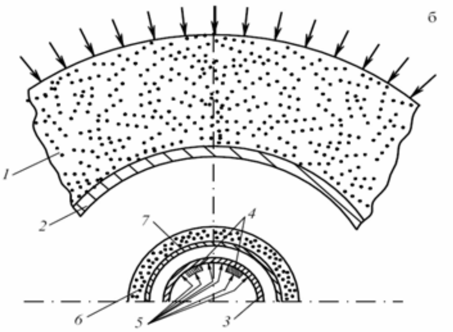

Рис. 4. Взрывное полусферическое устройство (а) и двухкаскадное взрывное полусферическое устройство (б). *1* — заряд ВВ; *2* — оболочка; *3* — экран; *4* — исследуемые образцы; *5* — электроконтактные датчики; *6* — заряд ВВ второго каскада; *7* — оболочка второго каскада.

Fig. 2 Two cascade hemispherical compression device (reference 3)

It was recognized that isentropic compression applies pressure gradually without heating the material, so there is no limit to the achievable compression if you have the driving energy. The challenge was the conversion of explosive-driven shocks to a smoothly increasing pressure ramp.

The original solution developed by Zababakhin was the use of "layering" developed for Sakharov's thermonuclear "sloyka", but equally applicable to anything that needs to be compressed at maximum possible densities for a given energy input [4]. This approach was "finessed" in the US by the Livermore (LLNL) laboratory, R.E. Kidder analysis of isentropic compression of shells for laser-driven ICF experiments [5] , and J. Nuckolls in particular, for high efficiency thermonuclear secondary implosions [6]. LLNL also developed mass production techniques using tape films to produce "graded" impactors with the desired pressure and density gradients for a particular application profile [7].

To illustrate the difference between isentropic and shock compression, we use Plutonium as a surrogate for Uranium. Fig. 3 shows both the isentropic and shock Hugoniot compressibility of delta phase Plutonium metal [8], requiring approximately 2 TPa to get an isentropic compression factor of 3 vs. an order of magnitude higher pressure (practically unattainable) using conventional flying plate shock compression techniques.

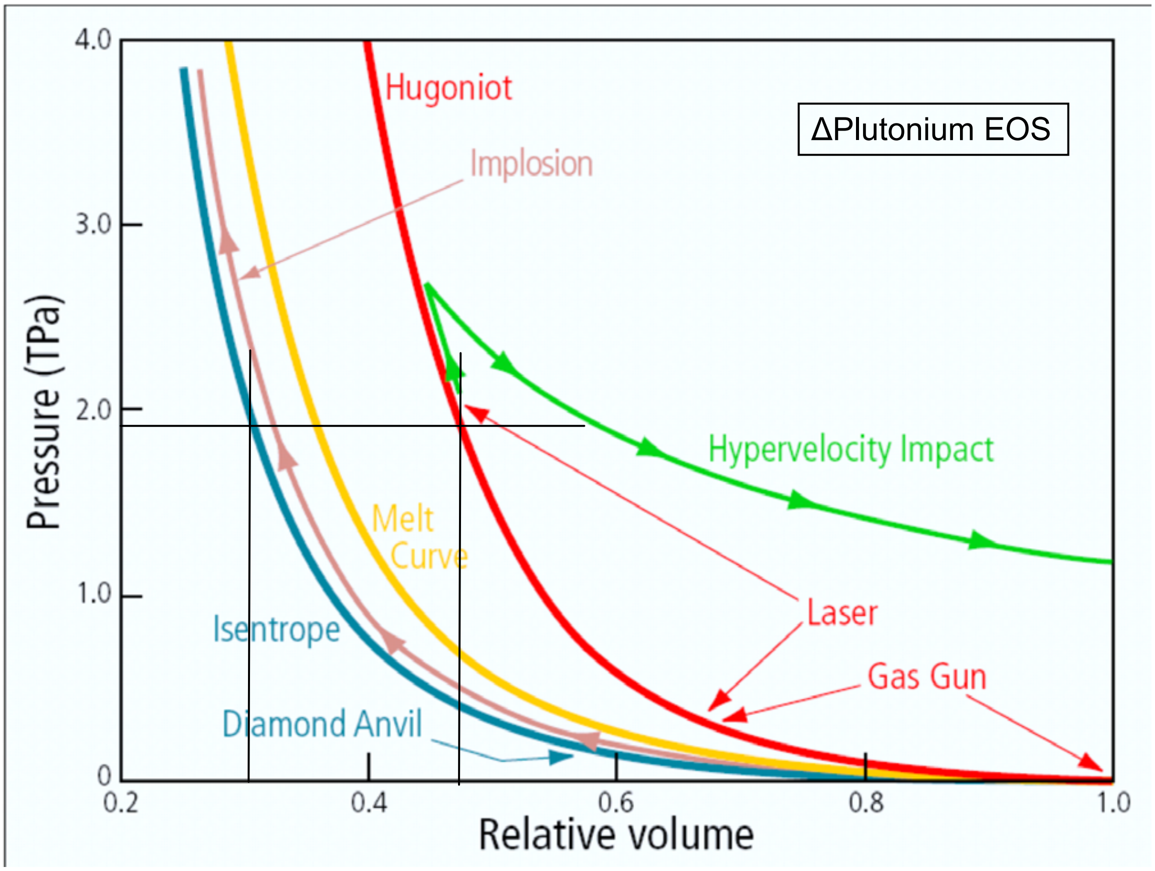

Fig. 3 Comparison of Isentropic and Shock Compression of Plutonium (reference 8)

Conclusion

The actual compression experiments described above in the "open" literature show that for the same explosive shock pressures, one can amplify the density increase through both spherical convergence and graded impactors to convert shocks to isentropic or quasi-isentropic pressure profile.

For bare HEU Uranium metal (or conversely, Plutonium), achieving an isentropic compression by a factor of approximately 3 reduces the amount of fissile material needed by a fission bomb by roughly a factor of 9. Of course, one can "finesse" additional reductions in fissile material mass through the use of Beryllium reflectors, boosting, and external initiation, which only makes matters worse as far as SQ numbers.

It is critical that we do not rely on exaggerated IAEA "SQ" numbers to be lulled into a false sense of security, and should not underestimate the capabilities of scientists and engineers in proliferant countries, such as Iran or North Korea in being able to apply similar knowledge and technology, which means that the "West" needs to have the proper metrics to evaluate timing and quantities for producing nuclear weapons.

References

[1] Al'tshuler, L.V. et al, "Investigation of Isentropic Compression and Equations of State of Fissionable Materials", Phys. Usp., 40, 101-102 (Jan 1997)
[2] Al'tshuler, L.V., Trunin, R.F., et al, "Development of Dynamic High Pressure Techniques in Russia", Phys. Usp., 42, 261 (Mar 1999)
[3] Al'tshuler, L.V. et al, "Explosive Laboratory Devices for Shock Wave Compression Studies", Phys. Usp., 39, 539-544 (May 1996)
[4] Zababakhin, E.I., "Shock Waves in Layered Systems", JETP, 49, 642-646 (Aug 1965)
[5] Kidder, R.E. "Laser-driven Compression of Hollow Shells: Power Requirements", Nuclear Fusion, 16, 3 (1976)
[6] Nuckolls, John,. "Contributions to the Genesis and Progress of Inertial Confinement Fusion", p. 12, in "Inertial Confinement Nuclear Fusion: A Historical Approach by its Pioneers", G. Velarde, ed., Foxwell and Davies (2007)
[7] Nguyen, J. et al, "Tape Casting Technique for fabrication of Graded-Density Impactors for Taylored Dynamic Compression", J. Appl. Physics, 100, 023508 (2006)
[8] Pollington, M., et al "Equations of State", Discovery -The Science & Technology Journal of AWE, No. 5 , p. 18 (2002)