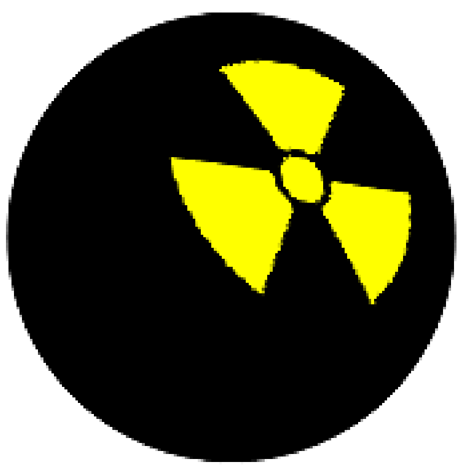
On Certain Design Aspects of the Implosion-Type Nuclear Weapon (ver. 1.1)

I.N. Galidakis,
Athens, Greece

November 2009



To the memory of my Father

Contents

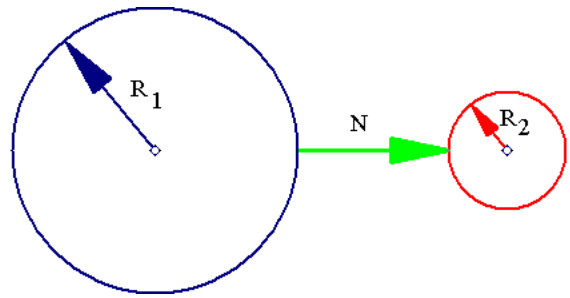


Figure 1: Implosion-type Nuclear Device

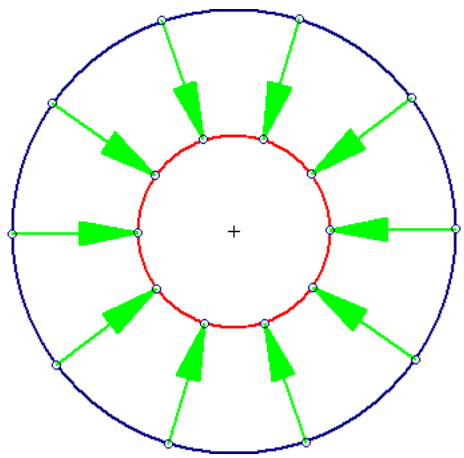


Figure 2: "Uniform" pressure against sub-critical mass

1 Introduction

An implosion type nuclear device is a process N which takes as input a spherical *sub-critical* mass M of fissionable material of radius R_1 and transforms it into a(n approximately) spherical *super-critical* mass of radius $R_2 < R_1$ (Fig. 1). A quick summary of the theory of operation for such a device, can be found in [23].

In order for the device N to achieve that, it has to apply a uniform and sufficient pressure on the surface of the sphere of fissionable mass with radius R_1, so that the mass is compressed into a sphere of radius $R_2 < R_1$.

"Uniform" means that the pressure has to be applied in a spherical manner, as in Fig. 2. "Sufficient" means that the pressure should be enough to reduce the radius from R_1 to R_2, with $R_2 \leq R_c < R_1$, with R_c being the critical radius of the fissionable mass M. R_c is a function of the fissionable element's critical density d_c, which in turn is a function of the purity of its refining process and other factors ([19]).

To facilitate uniformity, a special enclosure is constructed, called a *Shock-Wave Lens*. To facilitate sufficiency, the designer needs to calculate a minimum pressure, which, when delivered to the fissionable mass M, achieves a sufficient compression ratio. This minimum pressure is a function of the radius of the lens enclosure R_L and of the mass m_L of the conventional explosives in the lens enclosure, used to deliver pressure against the fissionable mass.

Both uniformity and sufficiency can be modelled using Maple [10] in the sections that follow. Geometrical figures were constructed with [9].

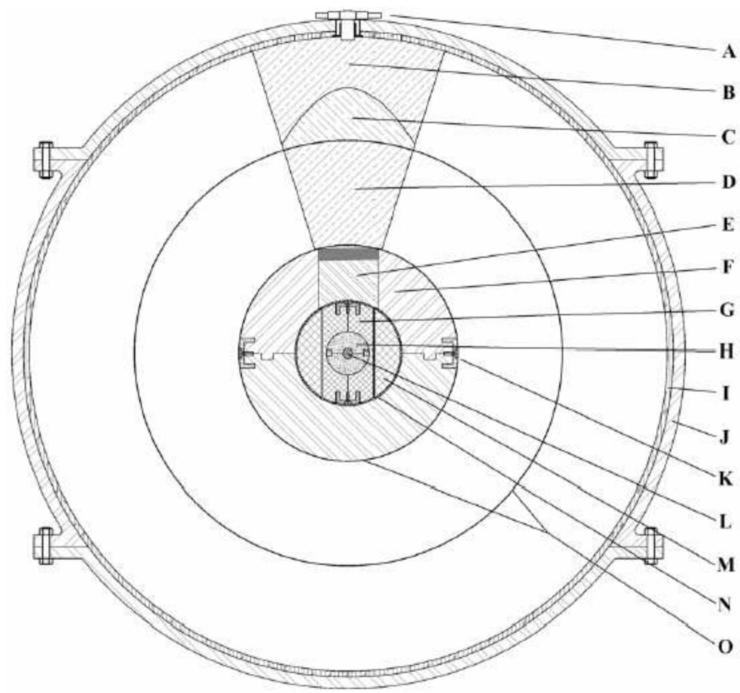


Figure 3: Internal structure diagram for implosion type weapon

1.1 The Design Parts

A plane section of the final device is shown on Fig. 3 ([12]).

A 1773 EBW detonator inserted into brass chimney sleeve (32)

B Comp B component of outer polygonal lens (32)

C Cone-shaped Baratol component of outer polygonal lens (32)

D Comp B inner polygonal charge (32)

E Removable aluminum pusher trap-door plug screwed into upper pusher hemisphere

F 18.5” diameter Aluminum pusher hemispheres (2)

G 4.375” diameter Tuballoy two-piece tamper plug

H 3.62” diameter Pu-239 hemispheres with 2.75 diameter jet ring

I 0.5” thick Cork lining

J 7-piece Y-1561 Duralumin sphere

K Aluminum cup holding pusher hemispheres together (4)

L 0.8” diameter Polonium-Beryllium Urchin initiator

M 8.75” diameter Tuballoy tamper sphere

N 9.0” diameter Boron plastic shell

O Felt padding layer under lenses and inner charges

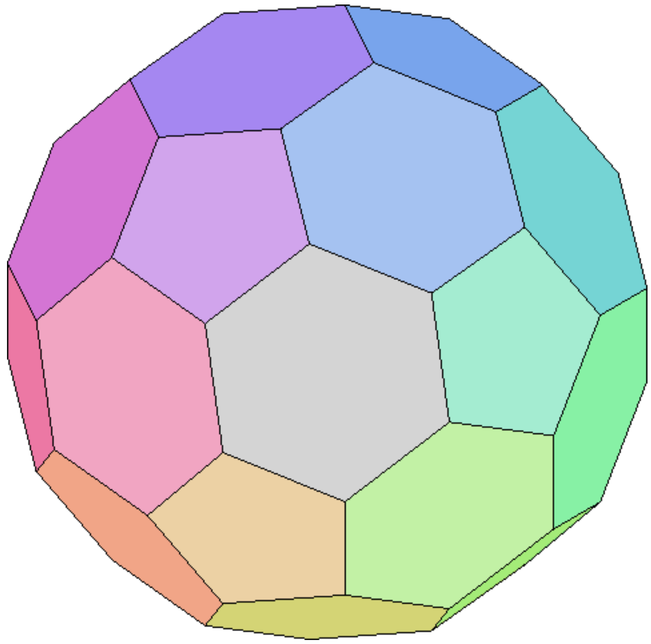


Figure 4: Truncated Icosahedron lens apparatus for implosion-type weapon

2 Uniformity: The Shock-Wave Lens Enclosure

The Shock-Wave Lens, for simplicity called just *lens* consists of an almost spherical shell of radius R_L, which focuses the explosive waves of the conventional explosives used to the center of the device, which contains the fissionable material, called *the pit*.

2.1 The Truncated Icosahedron Model

The lens usually is designed as a truncated icosahedron (Fig. 3) ([26], [8]), which is almost spherical ([22]). The interior of the truncated icosahedron may be viewed as a nested group of smaller truncated icosahedra resembling a honey-comb, therefore each vertical lens element is either a hexahedron or pentahedron pyramidal cone/frustum ([7]) of decreasing radius (Fig. 4).

On top and at the center of every hexagon and pentagon of the truncated icosahedron, there is a exploding-bridgewire detonator (A on Fig. 3)), which initiates the explosion ([20]).

Because the lens enclosure is totally symmetric with respect to the pit, each lens intersection with any plane normal to any radius will be a regular pentagon or hexagon whose symmetry group is either S_5 and S_6 respectively, therefore it can be modelled in two dimensions exactly, with the final model constructed by applying the principal symmetries of these two groups in three dimensions. Namely within each cone a complete rotation by 2π around the radial axis of the corresponding two-dimensional curve.

Inside each vertical lens cone there are two kinds of explosives used, a fast explosive with detonation speed $\vec{v}_1$, usually explosive Comp B ([18]) and a slow explosive with detonation speed $\vec{v}_2$, usually Baratol ([16]). Let R_A be the sub-radius of the fast explosive prior to the focusing lens and R_B be the inner radius of the fast explosive after the focusing lens, with $R_A + R_B = R_L$.

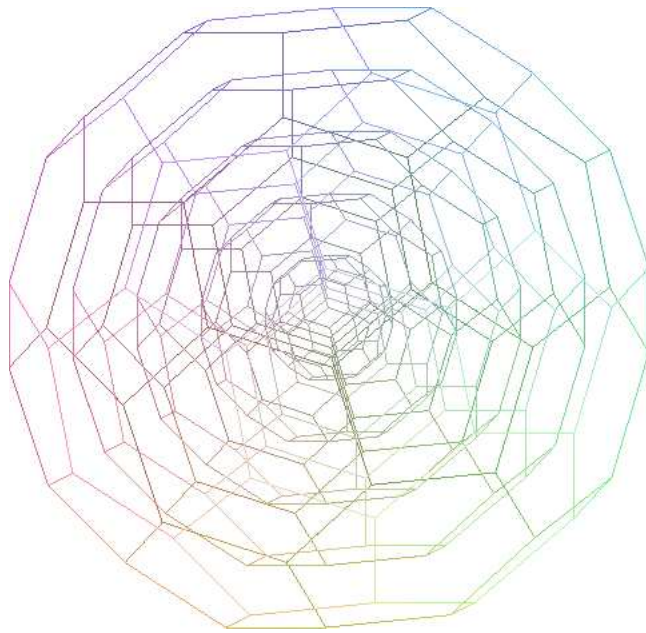


Figure 5: Internal structure diagram for truncated icosahedron lenses

2.2 Apical Angles of Hexagonal and Pentagonal Pyramidal Cones

If the vertices of the truncated icosahedron are placed on a sphere of radius $R_L = \sqrt{9\phi + 10}$, with $\phi = (1+\sqrt{5})/2$ ([26]), then all the edges have length 2. Call the circumradius of the hexagons and pentagons r_h and r_p respectively. The half apical angle θ_1 of the hexagonal cone and the half apical angle θ_2 of the pentagonal cone then satisfy the equations (Fig. 6):

$$\begin{aligned} R_L \sin(\theta_1) &= r_h \\ R_L \sin(\theta_2) &= r_p \end{aligned} \tag{2.1}$$

For the hexagonal cones, because all sub-triangles are equilateral, $r_h = 2$ ([5]), and for the pentagonal cones ([6]), $r_p = \sqrt{50 + 10\sqrt{5}}/5$. Equations (2.1) then give the half apical angles, as:

$$\begin{aligned} \theta_1 &= \arcsin\left(\frac{4}{\sqrt{58+18\sqrt{5}}}\right) \\ \theta_2 &= \arcsin\left(\frac{2\sqrt{50+10\sqrt{5}}}{5\sqrt{58+18\sqrt{5}}}\right) \end{aligned} \tag{2.2}$$

from which we get the apical angles of the hexagonal and pentagonal cones:

$$\begin{aligned} \Theta_1 &= 2\theta_1 \sim 47.60036521 \ \text{ degrees} \\ \Theta_2 &= 2\theta_2 \sim 40.15350256 \ \text{ degrees} \end{aligned} \tag{2.3}$$

The angles θ_1, θ_2 are of course invariant under R_L.

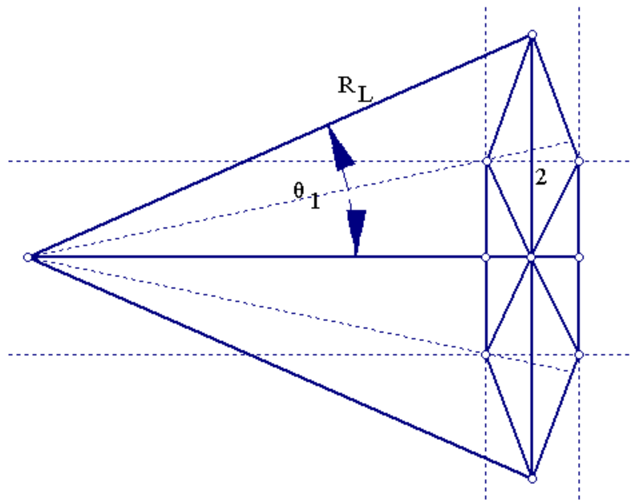


Figure 6: Half apical angle for a hexagonal pyramidal cone

2.3 The Lens Concept

Each cone has either five or six neighbors which behave exactly the same. All cones are synchronized in the explosion, therefore the shock-waves propagate only towards the pit and never cross cone boundaries, because they are cancelled by the shock-waves of the neighboring cones.

Call $(x(t), y(t))$ a point of the shock-wave front at time t after detonation at $t = 0$. Clearly $x(0) = 0$ and $y(0) = R_L$. Prior to focusing, $\rho_1(t) = \vec{v}_1 t$ is the wave front distance from the detonator at $(0, R_L)$, as a function of time for the fast explosive. Therefore the shock-waves for the fast explosive prior to focusing satisfy the equations:

$$x(t)^2 + (y(t) - R_L)^2 = (\vec{v}_1 t)^2 = \rho_1(t)^2 \tag{2.4}$$

These shock-waves are shown on Fig. 7. The object of the lens is to focus the waves in the form shown on Fig. 8.

To facilitate focusing the shock-waves must transition from satisfying (2.4) to satisfying the equations,

$$x(t)^2 + y(t)^2 = (R_L - \vec{v}_1 t)^2 = \rho_2(t)^2 \tag{2.5}$$

2.4 The Hexagonal Lens

The transition is achieved by adding a slow explosive with an appropriate shape Y_1 which will modify the shock-waves from satisfying (2.4) to satisfying (2.5) ([4], [2]). This is a classical problem in wave propagation, which was investigated first by Descartes for optical waves ([13]). The solution is called a Cartesian Oval ([14]). Note that on [4] where the author wants a plane wave, the resulting shape is a hyperbola, which is one of the degenerate cases of a Cartesian Oval ([14]).

In order for Y_1 to effectively work as a lens between the detonator and the pit, first one models a lens consisting of two media and then one modifies the design to minimize the second medium, in this case the slow explosive, Baratol.

The general equation of the Cartesian Oval is:

$$m\rho_1 + n\rho_2 = k \tag{2.6}$$

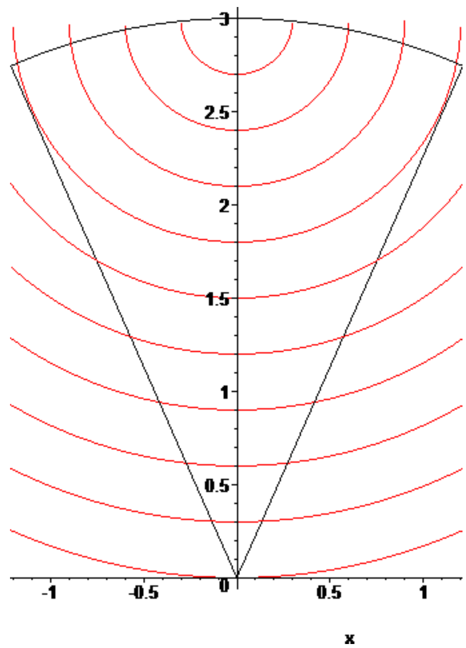


Figure 7: Shock-waves after detonation prior to focusing

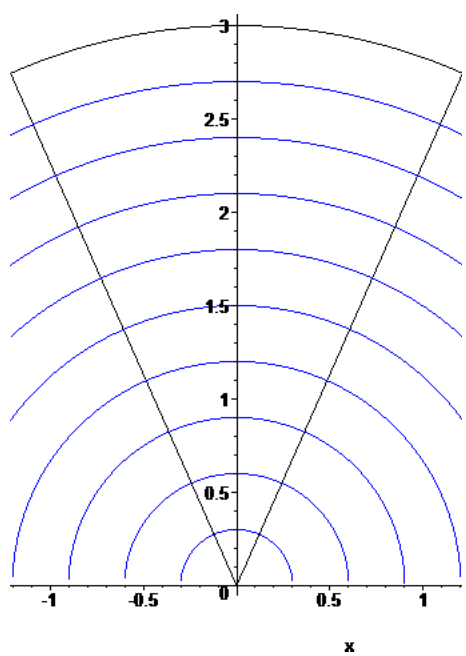


Figure 8: Shock-waves after focusing

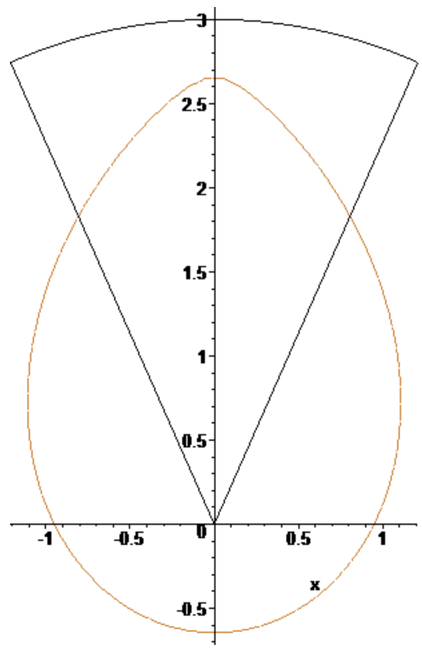


Figure 9: Cartesian Oval lens for two foci, at $(0, R_L)$ and $(0, 0)$, with $R_L = 3$ and $r \sim 0.11$ for hexagonal lens

For a vertical cone model with the detonator at $(0, R_L)$ and the pit at $(0, 0)$ and in view of equations (2.4) and (2.5), equation (2.6) becomes:

$$m\sqrt{x^2 + (y - R_L)^2} + n\sqrt{x^2 + y^2} = k \tag{2.7}$$

Calling $\rho_1 = rR_L$, with $0 < r < 1$, we have $\rho_2 = (1-r)R_L$ and then $k = m\rho_1 + n\rho_2 = (mr + n(1-r))R_L$.

Without loss of generality we can take $m = 1$. Note ([14]) that $n/m = \vec{v}_1/\vec{v}_2$, hence for the two explosives, Comp B and Baratol, which have $\vec{v}_1 = 8050m/s$ and $\vec{v}_2 = 4900m/s$ respectively, we get $n = 23/14$.

In view of the above and for $R_L = 3m$, (2.7) becomes:

$$\sqrt{x^2 + y^2 - 6y + 9} + \frac{23}{14}\sqrt{x^2 + y^2} = \frac{-27r + 69}{14} \tag{2.8}$$

Calling the solution of equation (2.8) y, note that it will necessarily have to be radially symmetric, because it transitions a radially symmetric shock-wave into another radially symmetric shock-wave.

The resultant curve is shown on Fig. 9.

From equations (2.6), (2.7) and (2.8) it is obvious that the shape of Y is a function of the speed of the explosives used n/m, r and hence of R_A and finally of R_B. Different explosives and radii R_A and R_B will require a different shaped Y, that's why in practical terms the exact shape is machined using iteration ([11]), by checking $y(r, x_1)$ and $R_B \cos(\theta_1)$ for equality, with $x_1 \in [0, 1]$ a solution of the equation $y(r, x) = x\tan(\pi/2 - \theta_1)$, which must hold at the edge of the cone. For a given R_B one chooses an r which closely matches R_B, tests the lens, then repeats. The iteration is complete when r satisfies the equation:

$$y(r, x_1) = R_B \cos(\theta_1) \tag{2.9}$$

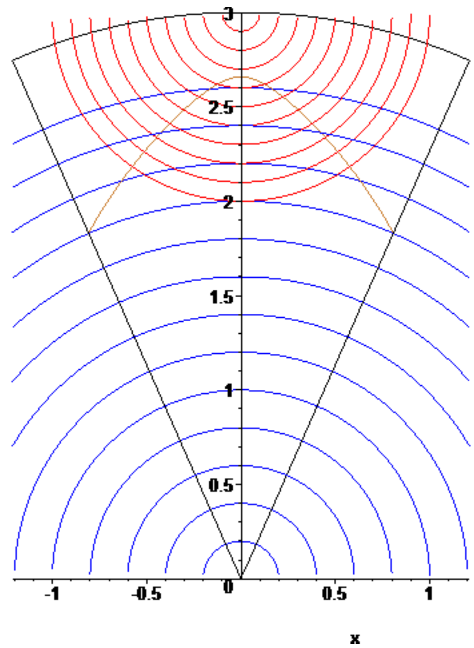


Figure 10: Shock-waves before focusing (red), after focusing (blue) and transition curve $y(r, x)$ (gold), with $R_A = 1m$, $R_B = 2m$, $r \sim 0.11$ and $n = 23/14$ for hexagonal lens

The figures on this document have been created after iterating x_1 and r twice, to match an $R_B \sim 2R_L/3$.

Once the shock-waves have been focused below the transition surface for the hexagonal and pentagonal cones to a base extent of r_h and r_p respectively, there is no need to add more Baratol slow explosive below R_B. Therefore, from a construction/practical standpoint, the Baratol explosive can be only an additional "slice" (called "ice-cream cone"), added on top of the fast Comp B explosive inside every cone at radius R_B as shown on Fig. 11. Ignoring for a moment the tamper, pusher and the other elements which lie close to the pit (F,G,H on Fig. 3), this means that the internal Comp B explosive can be a solid sphere of radius R_B.

By the symmetry of the group S_6, the required surface Y will then be the curve y of equation (2.8) revolved around the y-axis on Fig. 9, by 2π radians. This surface, Y along with the hexagonal cone is shown on Fig. 12.

2.5 The Pentagonal Lens

The analysis for the pentagonal lens is entirely similar, with θ_1 replaced by θ_2 and S_6 by S_5. Note that the hexagonal and pentagonal lenses need to be synchronized after detonation, which means that the Comp B explosive at radius $R_B = 2R_L/3$ needs to ignite at the same time t_B, it ignites for the hexagonal lens. t_B is given as,

$$t_B = \frac{rR_L}{\vec{v}_1} + \frac{\left(\frac{1}{3} - r\right) R_L}{\vec{v}_2}$$

Therefore we can use the same r and hence the same Cartesian Oval for both hexagonal and pentagonal lenses, adjusting only the height in the pentagonal lenses. Intuitively this is correct, because the Cartesian Oval as a locus is invariant under different cone boundaries. The results for the pentagonal lens are shown on Figs. 13, 14, 15 and 16.

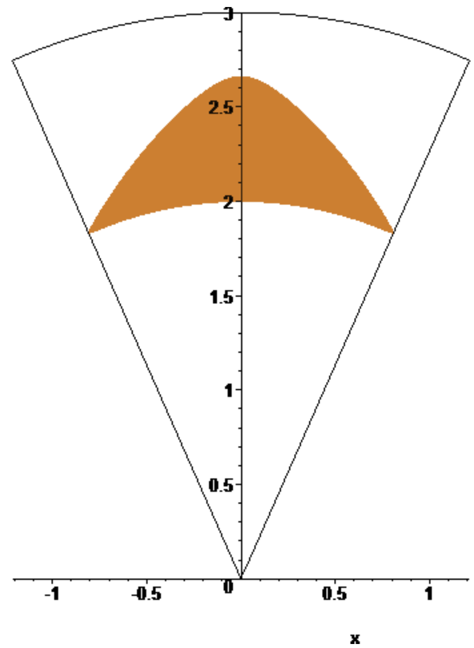


Figure 11: “Ice-cream cone” with Baratol explosive at radius $R_B = 2m$ for hexagonal lens

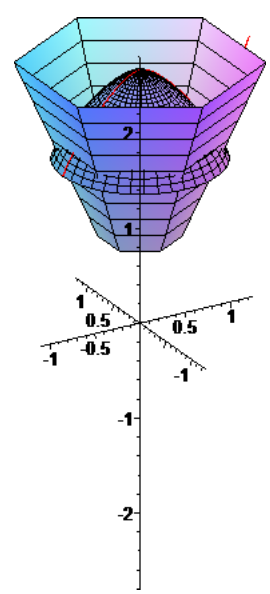


Figure 12: Hexagonal lens with Baratol explosive surface $Y(r, x)$ at radius $R_B = 2m$

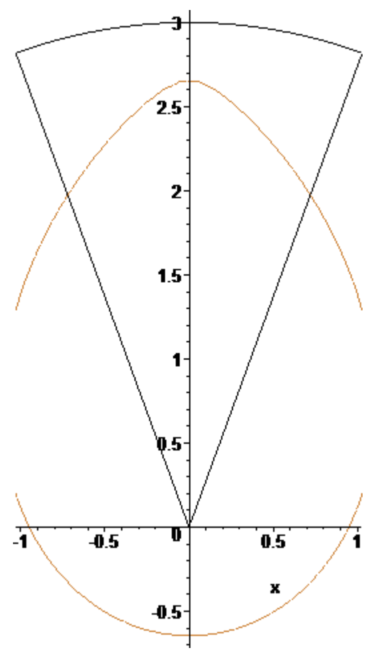


Figure 13: Cartesian Oval lens for two foci, at $(0, R_L)$ and $(0, 0)$, with $R_L = 3$ and $r \sim 0.11$ for pentagonal lens

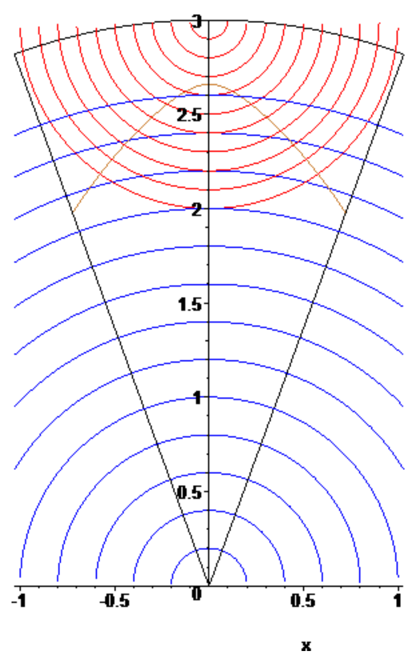


Figure 14: Shock-waves before focusing (red), after focusing (blue) and transition curve $y(r, x)$ (gold), with $R_A = 1m$, $R_B = 2m$, $r \sim 0.11$ and $n = 23/14$ for pentagonal lens

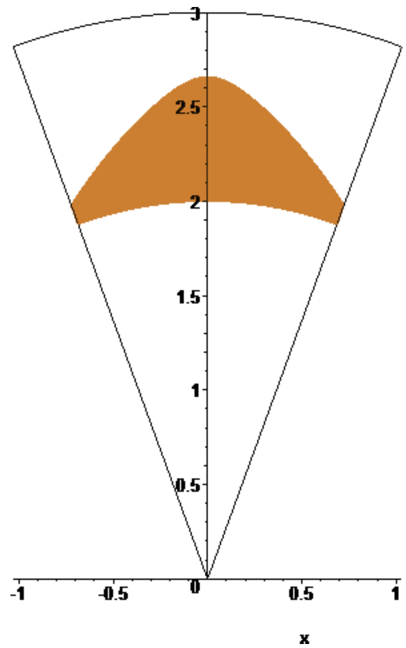


Figure 15: “Ice-cream cone” with Baratol explosive at radius $R_B = 2m$ for pentagonal lens

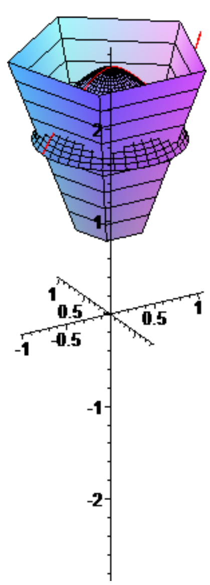


Figure 16: Pentagonal lens with Baratol explosive surface $Y(r, x)$ at radius $R_B = 2m$

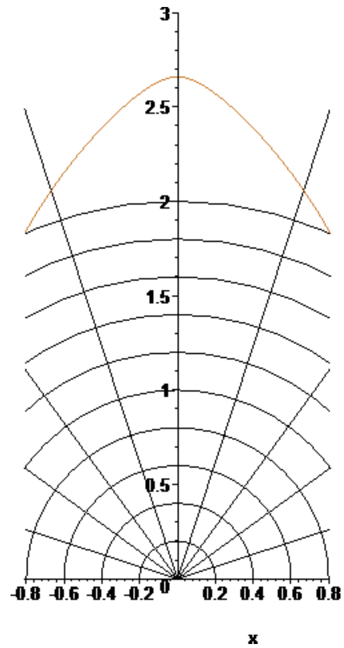


Figure 17: Transition curve $y = R(\theta)$ in Polar coordinates

2.6 The Lens Curve in Polar Coordinates

Equation (2.8) can be transformed to Polar form, using the substitutions $x = R\cos(\theta)$ and $y = R\sin(\theta)$ and solving for R in terms of θ. Because the resultant expression will be a quartic, in most cases there will be no closed form expression, but because polar coordinates are more suitable for machining radially symmetric surfaces, a numerical polar form may be preferable. For the example given above, the polar equation of the transition surface to five decimal places and after two iterations for the lenses is,

$$\begin{aligned} R(\theta) = &- 1.76576\sin(\theta) + 4.55343 - 0.84084 \cdot 10^{-10} \\ &\cdot \sqrt{0.441 \cdot 10^{21}\sin(\theta)^2 - 0.22744 \cdot 10^{22}\sin(\theta) + 0.18358 \cdot 10^{22}} \end{aligned} \tag{2.10}$$

with $\pi/2 - \theta_1 \leq \theta \leq \pi/2 + \theta_1$ for the hexagonal lens and with $\pi/2 - \theta_2 \leq \theta \leq \pi/2 + \theta_2$ for the pentagonal lens

The resultant shape is shown on Fig. 17.

Machinable versions of Baratol now exist ([1]). To machine the shape, one sets $r = r_1$ in equation (2.8) and considers incremental approximations θ_j, $j \in \{0, 1, 2, ..., N\}$ on equation (2.10). The required approximate radial distances to the surface will be given as $R(\theta_j)$, and j as above in two dimensions.

Using equation (2.10) for example, if the total machining steps on the interval $[\pi/2 - \theta_1, \pi/2]$ are N, then for a tolerance of $\Delta R \leq 10^{-3}m = 1mm$ one needs $N \geq 57$ steps, which corresponds to $\Delta\theta \leq 0.41754$ degrees per step size to five decimal places.

The hexagonal and pentagonal lenses are shown in place on Figs. 18 and 19.

The higher the Baratol lenses are positioned inside the corresponding pentagonal or hexagonal cone, the greater the delivered force of the Comp B fast explosive.

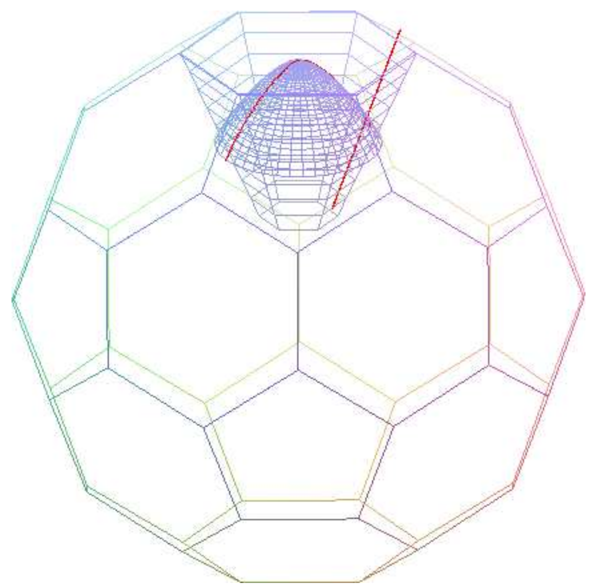


Figure 18: Hexagonal lens in place

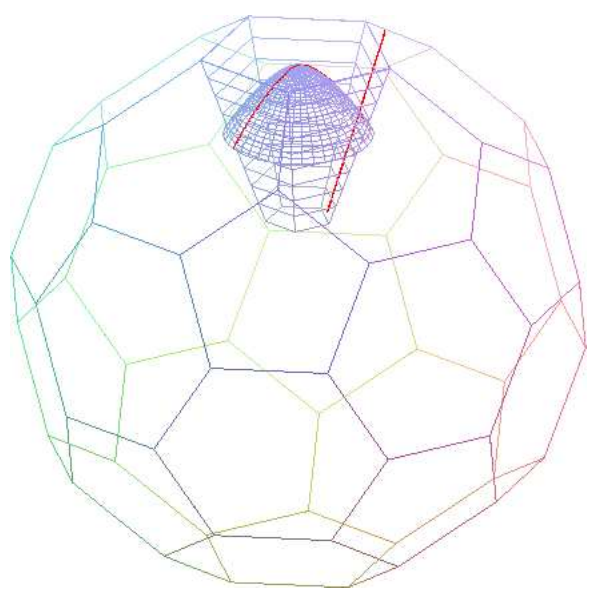


Figure 19: Pentagonal lens in place

3 Sufficiency: The Calculation of Pressure

To simplify the calculations, assume that the tamper and pusher elements (F and M on Fig. 3) are not present. For the final calculation, we can easily adjust for these. We can also assume that instead of Comp B, we are using TNT, for which we know its explosive strength.

3.1 Explosive Strength

If the radius of the lens is R_L and the radius of the fissionable mass is R_F, then the total volume of the lens is,

$$V_L = \frac{4}{3}\pi \left(R_L^3 - R_F^3\right) \quad (m^3) \tag{3.1}$$

With a density of $\rho \sim 1.65 g/cm^3$ (Comp B and TNT have similar densities), the total mass m_L of the lens will be,

$$m_L = \rho \cdot V_L \quad (kg) \tag{3.2}$$

TNT has an explosive strength ([21]) of $s \sim 2.72 \cdot 10^6 J/kg$, hence the total explosive strength S_L of the lens will be:

$$S_L = s \cdot m_L \quad (Pa \cdot m^3) \tag{3.3}$$

Call the volume of the fissionable element V_F. Then the total pressure P_L delivered to the fissionable element by the lens will be:

$$P_L = \frac{S_L}{V_F} \quad (Pa) \tag{3.4}$$

3.2 Radial Bounds for Criticality of the Fissionable Mass

Plutonium's bulk modulus K_{Pu} ([17]) can be calculated by its Young and Shear moduli E_{Pu} and G_{Pu} respectively ([25]), as:

$$K = \frac{EG}{3(3G - E)} \tag{3.5}$$

Equation (3.5) approximates iron's bulk modulus ([24]) quite well, giving a $K_{Fe} \sim 164GPa$ versus a reported $K_{Fe} \sim 170GPa$. For Plutonium (3.5) gives $K_{Pu} \sim 41.69GPa$, versus a reported $K_{Pu} \sim 55GPa$ by the Los Alamos labs ([3]). To be on the safe side, we can take $K_{Pu} \sim 60GPa$. To be totally safe, we can take iron's bulk modulus $K_{Fe} \sim 160GPa$.

Assuming we are in possession of the required weapon-grade Plutonium 239 sphere, we need only increase its density by a factor of 2 ([22]) in order for fission to start, although advanced designs can reach higher densities ([11]). If the initial and final densities are ρ_1 and ρ_2 corresponding to initial and final volumes V_1 and V_2, then,

$$\begin{aligned} \rho_2 &\geq 2\rho_1 \Rightarrow \\ \frac{m}{V_2} &\geq 2\frac{m}{V_1} \Rightarrow \\ V_2 &\leq \frac{1}{2}V_1 \end{aligned} \tag{3.6}$$

The above will require a pressure increase of at least $K_{Pu}/2$ ([17]). Using (3.4) we get:

$$P_L \geq \frac{K_{Pu}}{2} \tag{3.7}$$

Substituting equation (3.4) in (3.7), we find:

$$\frac{s\rho\left(R_L^3 - R_F^3\right)}{R_F^3} \geq \frac{K_{Pu}}{2} \tag{3.8}$$

Substituting $s = 2.72 \cdot 10^6 J/kg$, $\rho = 1650 kg/m^3$, $R_F = 5/100m$, $K_{Pu} = 60GPa$ into and solving equation (3.8) for R_L we get $R_L \geq 9.88cm$. Hence for this case ($R_F = 5cm$), $\Delta R \geq R_L - R_F = 9.88cm - 5cm = 4.88cm$, which gives a minimum bound for the radial difference between the two spheres, of the fissionable material and of the lens, which corresponds to an approximately minimum lens mass of $\Delta m_L = \rho \Delta V = 4/3\pi\rho(R_L^3 - R_F^3)$, which gives $\Delta m_L \geq 5.71215kg$ of TNT explosive.

If a tamper and pusher which are made of Tuballoy and aluminum respectively are used as in Fig. 3, it suffices to take $R'_F = R_P$ where R_P is the radius of the pusher and $K_N \sim \max\{K_{Pu}, K_U, K_{Al}\} = 100GPa$ ([15], [27]), because this is space which needs to be compressed altogether. In this case $R_P \sim 23.5cm$ and solving equation (3.8) with otherwise the same parameters, gives $\Delta R \geq 54.13cm$ and $\Delta m_L \geq 988.9kg$ of TNT explosive.

A minimum diameter for the device shown on Fig. 3 is then, $D_N = 2 \cdot (R_P + \Delta R) = 2 \cdot (23.5cm + 54.13cm) \sim 1.55m$, which is fairly consistent with the size of Fat Man as shown in [22] ([11] gives $1.4m$). For this D_N and for $r \sim 0.11386$ and after two iterations for the hexagonal lens, we get $R_A \sim 25.87666cm$ and $R_B \sim 51.75333cm$, which is approximately twice the radius R_P of the pusher F shown on the figure.

To increase the device's detonation pressure even further, one can move the Baratol lens closer to the top, which is made possible by using a smaller r in the iteration of section 2.

4 Assembly and Arming

The external Durallumin assembly is shown on Fig. 20 in meters.

Note that the assembly sequence is quite complicated. The device's difficult part is the construction of the lenses. For this, one constructs 32 separate frustums [7] (20 hexagonal and 12 pentagonal ones) as in Figs. 19 20, which contain the lenses. The frustums are then assembled on top of the pusher sphere completing the truncated icosahedron.

One hexagonal cone is left uncovered and its contents can be removed based on the diagram of Fig. 3.

This includes all the elements inside the cone shown on the diagram. To arm the device, one first places the polonium-beryllium urchin initiator (L) at the center of one of the two plutonium hemispheres (H), then joins the two hemispheres and inserts the resulting sphere into one of the two semi-cylinders of Tuballoy two-piece tamper plug (G), joins the two pieces together and screws the resulting cylinder into the removable aluminum pusher trap-door plug (E). The resulting segment is then lowered into the actual pit and screwed against the pusher element (F). Then the last hexagonal lens is put into place, the last 7-piece Y-1561 Duralumin (top) cap (J) is placed on the resulting sphere and the last 1773 EBW detonator (A) inserted into brass chimney sleeve.

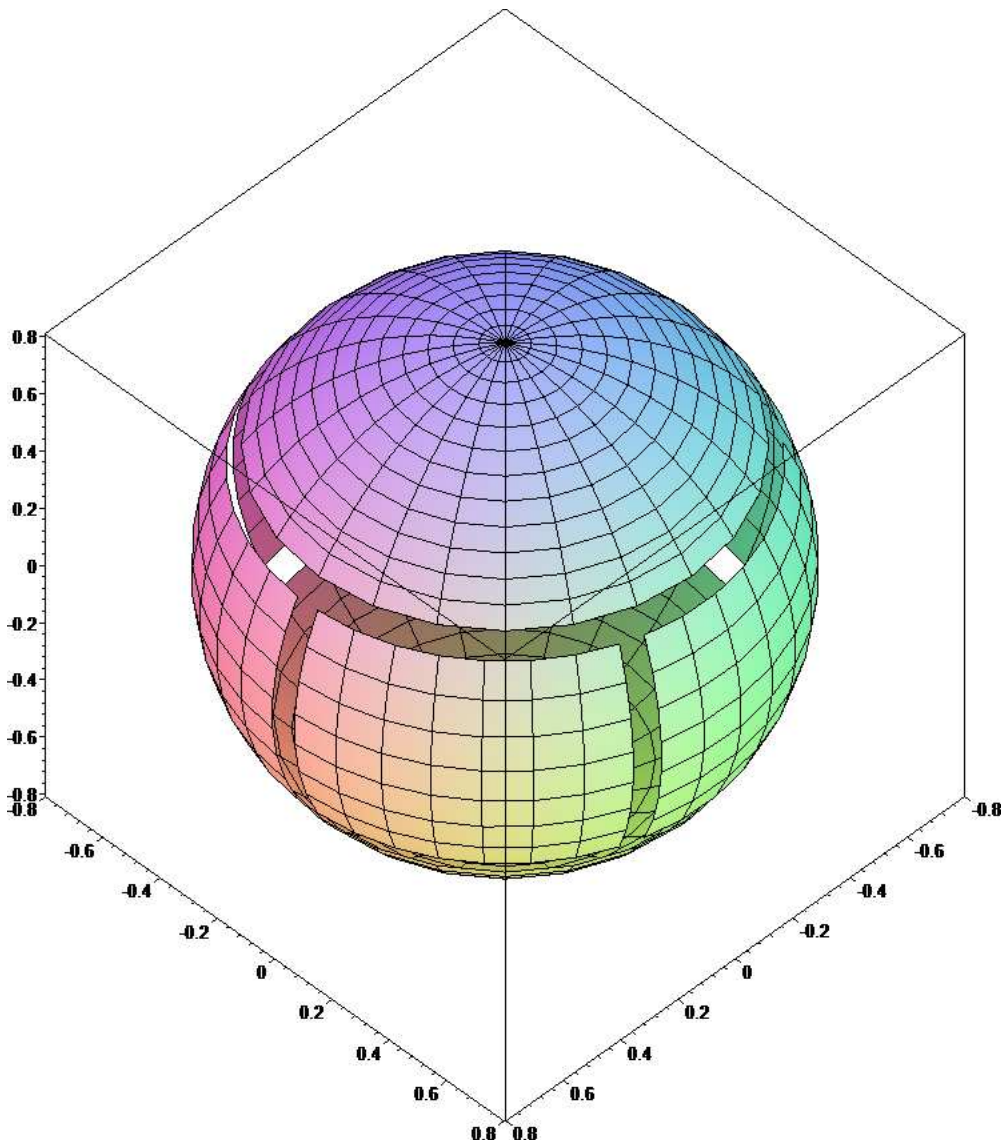


Figure 20: External Durallumin sphere assembly for the device shown on Fig. 3

5 Bibliography

References

[1] Theodore C. Crawford. High Explosive Compound. US Patent 3,956,039, 1976.

[2] T. Goto, Y. Syono, J. Nakai, and Y. Nakagawa. Shock Compression Experiments in Solids using High Explosives. *The Research Institute for Iron, Steel and Other Metals*, pages 186–199, 1975.

[3] Los Alamos National Laboratory. α-plutonium's elastic properties. Website, 2004. http://arq.lanl.gov/source/orgs/nmt/nmtdo/AQarchive/05spring/alphapu.ht%ml.

[4] Stanley P. March. Explosive Plane Wave Lens. US Patent 4,729,318, 1988.

[5] MathWorld. Hexagon. Website, 2004. http://mathworld.wolfram.com/Hexagon.html.

[6] MathWorld. Pentagon. Website, 2004. http://mathworld.wolfram.com/Pentagon.html.

[7] MathWorld. Pyramidal Frustum. Website, 2004. http://mathworld.wolfram.com/PyramidalFrustum.html.

[8] MathWorld. Truncated Icosahedron. Website, 2004. http://mathworld.wolfram.com/TruncatedIcosahedron.html.

[9] P. Pamfilos. Euclidraw. Website, 2004. http://www.euclidraw.com.

[10] D. Redfern. *The Maple Handbook*. Springer-Verlag, 1996.

[11] Carey Sublette. Elements of Fission Weapon Design. Website, 1999. http://nuclearweaponarchive.org/Nwfaq/Nfaq4-1.html.

[12] Unknown. Cross section Drawing of the Y-1561 Implosion Sphere. Website, 2004. http://www.designnews.com/file/2437-Cross_section_drawing_of_the_Y_1561%_implosion_sphere.pdf.

[13] Thomas Walmann. Some useful formulas for lenses. Website, 2004. http://folk.uio.no/walmann/Publications/Master/node7.html.

[14] Jan Wassenaar. Cartesian oval. Website, 2004. http://www.2dcurves.com/quartic/quarticct.html.

[15] Wikipedia. Aluminum. Website, 2004. http://en.wikipedia.org/wiki/Aluminum.

[16] Wikipedia. Baratol Explosive. Website, 2004. http://en.wikipedia.org/wiki/Baratol_(explosive).

[17] Wikipedia. Bulk Modulus. Website, 2004. http://en.wikipedia.org/wiki/Bulk_modulus.

[18] Wikipedia. Composition B Explosive. Website, 2004. http://en.wikipedia.org/wiki/Composition_B.

[19] Wikipedia. Critical Mass. Website, 2004. http://en.wikipedia.org/wiki/Critical_mass.

[20] Wikipedia. Explosive Bridgewire detonator. Website, 2004. http://en.wikipedia.org/wiki/Exploding-bridgewire_detonator.

[21] Wikipedia. Explosive Strength. Website, 2004. http://en.wikipedia.org/wiki/Strength_(explosive).

[22] Wikipedia. Fat Man. Website, 2004. http://en.wikipedia.org/wiki/Fat_Man.

[23] Wikipedia. Implosion Weapon. Website, 2004. http://en.wikipedia.org/wiki/Nuclear_weapon_design.

[24] Wikipedia. Iron. Website, 2004. http://en.wikipedia.org/wiki/Iron.

[25] Wikipedia. Plutonium. Website, 2004. http://en.wikipedia.org/wiki/Plutonium.

[26] Wikipedia. Truncated Icosahedron. Website, 2004. http://en.wikipedia.org/wiki/Truncated_icosahedron.

[27] Wikipedia. Uranium. Website, 2004. http://en.wikipedia.org/wiki/Uranium.