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Appendix C

DESIGN AND FEASIBILITY OF SUPERHARD SILOS[1]

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A superhard silo is a structure designed to protect an enclosed missile from nuclear blast at ranges larger than the inner bowl radius of the crater excavated by an attacking nuclear warhead, so that the primary destruction mechanism becomes cratering (i.e. the fracturing and excavation occurring within the inner bowl of the crater) rather than blast wave pressure. Analysis of published DoD comments indicates that superhard silos require resistance to a peak blast pressure of perhaps 7,500 atm (appendix A).

A superhard silo may be mechanically approximated as a double-walled cylinder, probably with near-hemispherical end caps of the same construction. The inner wall of the silo is likely to be a heavy-wall steel tube, while the outer wall would be a somewhat thinner-wall steel tube. The space between the walls would be filled with steel reinforcement, high-strength concrete, and reinforcing wire.[2] The silo would be sited in hard rock, perhaps centered within a lattice of drilled holes to facilitate rock crushing and ground blast wave energy absorption.

Static stress calculations have been performed for a potential superhard silo that could be appropriate for a single-warhead ICBM; the silo for a heavy ICBM would be obtained by geometric scaling. The silo is taken to have an inner radius of 1 meter and an outer radius of 2 meters. The inner wall is assumed to have a thickness of 20 centimeters, while the outer wall is assumed to have a thickness of 10 centimeters. The space between the walls is assumed to be filled with wire loaded with high-strength concrete, with an average elastic modulus ⅓ the steel elastic modulus. An applied hydrostatic compressive stress S results in circumferential compressive stresses of $4.5S$ at the inner wall of the inner cylinder, $1.4S$ at the inner wall of the concrete, and $3.1S$ at the inner wall of the outer cylinder. The axial stresses are approximately ½ the circumferential stresses.

Static compressive failure loads of heat-treated high-toughness plate steels can exceed 10,000 atm while simultaneously exhibiting reasonable ductility. Micro-alloyed high strength steels with very low free carbon levels have somewhat lower strengths but are tougher and exhibit substantially higher plastic deformation before failure. Marginally austenitic and TRIP steels can exhibit particularly high strengths and deformations, but tend to be expensive and/or difficult to work. The compressive failure stress, without subtraction of the effective hydrostatic stress or the effect of wire reinforcement, in optimized high strength concrete exceeds 1,000 atm. Comparison of the induced stresses with static failure stresses suggests that such silos should be able to survive static pressures approaching 2,000 atm.[3]

But the blast wave is not static. It has a virtually instantaneous rise time, and a decay time constant of $1–3{\cdot}10^{-3}$ seconds. The high-stress behavior, several times the nominal yield stress, of engineering materials on such time scales is not well documented in the open literature, but it is known that these materials may survive stresses up to several times their static failure stresses under such loading conditions.

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The applied stresses are far beyond the yield point of the materials involved, taking the silo into a mechanical regime dominated by the high-rate deformation.

Under such stresses the silo walls deform, the concrete crumbles and debonds from the reinforcing wire, and the silo yields, but the brevity of the blast wave does not allow time for incipient failures to propagate and grow. Shock-isolation techniques (shock absorbers, foam, enclosure of the missile in a canister) then protect the missile from the residual blast wave, after attenuation in the rock and concrete. Comments from US Defense Nuclear Agency officials, and non-nuclear blast tests using reduced scale models, suggest that the combination of short time constant strengthening and plastic deformation may allow such a silo to survive peak blast pressures three to four times the static failure limit, or perhaps 6,000–8,000 atm.[4]

NOTES AND REFERENCES

1. The design characteristics of hard and superhard silos are discussed in Barbara G. Levi, Mark Sakitt, and Art Hobson, eds., *The Future of Land-Based Strategic Missiles* (New York: American Institute of Physics, 1989), pp.239–256. This appendix summarizes that discussion.

2. This structure, and its response to non-nuclear blast tests, is described in interviews with Air Force officials, in Edgar Ulsamer, "The Prospect for Superhard Silos," *Air Force Magazine*, January 1984, pp. 74-77.

3. It is far easier to design silos able to survive static blast pressures of 1000 atm, and may even be possible to mass produce their critical components at relatively low cost.

4. Air Force Assistant Secretary Thomas E. Cooper, quoted in "SS-18 Not Capable of 250-foot CEP," *Defense Daily*, 22 May 1985, p.121; Edgar Ulsamer, "The Prospect for Superhard Silos," *Air Force Magazine*, January 1984, pp.74–77; "Midgetman Tests on Basing Alternatives," *Jane's Defense Weekly*, 24 March 1984, p.427; *ICBM Modernization Program, Annual Progress Report*, Department of Defense, Washington DC, 15 January 1985, pp.9-10; Gerald E. Marsch, "Is Smaller Better?" *Bulletin of the Atomic Scientists*, February 1984, p.10; US Air Force, *FY 1985 Budget Estimates*, p.13; US Air Force, *MX—Closely Spaced Basing*, 20 July 1982, p.14; David C. Morrison, "ICBM Vulnerability," *Bulletin of the Atomic Scientists*, pp.26–28; Donald A. Hicks, "ICBM Modernization," *International Security*, Fall 1987, p.180; John C. Toomay, "Strategic Forces Rationale," *International Security*, Fall 1987, p.197. Many however doubt the feasibility of superhard silos; for example, William M. Arkin, "Going With Small ICBMs," *Bulletin of the Atomic Scientists*, May 1984, , p.8.