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COSMIC BOMBARDMENT V: THREAT OBJECT-DISPERSING APPROACHES TO ACTIVE PLANETARY DEFENSE*

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ABSTRACT

Earth-impacting comets and asteroids with diameters ~0.03 – ~10 km pose the greatest threats to the terrestrial biosphere in terms of impact frequency-weighted impact consequences, and thus are of most concern to designers of active planetary defenses. Specific gravitational binding energies of such objects range from ~10^{-7} to 10^{-2} J/gm, and are small compared with the specific energies of ~$1x10^3$ to ~$3x10^3$ J/gm required to vaporize objects of typical composition or the specific energies required to pulverize them, which are ~10^{-1} to ~10 J/gm. All of these are small compared to the specific kinetic energy of these objects in the Earth-centered frame, which is ~$2x10^5$ to ~$2x10^6$ J/gm. The prospect naturally arises of negating all such threats by deflecting, pulverizing or vaporizing the objects.

Pulverization-with-dispersal is an attractive option of reasonable defensive robustness, and can be implemented with a mass-multiplication efficiencies of ~10^5 to 10^7, i.e., a unit mass of optimally designed pulverization equipment can pulverize and disperse 10^5 to 10^7 times its own mass of threat object. Examples of such equipments – which employ no explosives of any type – are given. With contemporary technology, these appear adequate to negate threats from cometary objects of diameters ≤0.6 km, stony asteroidal objects of diameters ≤0.125 km and nickel-iron asteroidal objects with diameters ≤0.05 km, using equipment which may be deployed on single Energiya*-class booster. Multi-booster systems using*

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only existing space-launch hardware can negate threat objects of ~3 times greater diameter.

Vaporization is the maximally robust defensive option, and may be invoked to negate threat objects not observed until little time is left until Earth-strike, and pulverization-with-dispersal has proven inadequate. Kinetic energy-based vaporization with non-nuclear equipments based on contemporary technology and use of existing space-launch assets appear adequate to negate cometary threats of diameters $\leq$*0.1 km, stony asteroidal threats of diameters* $\leq$*0.035 km and nickel-iron asteroidal threats with diameters* $\leq$*0.025 km.*

Physically larger threats may be vaporized with nuclear explosives, which with contemporary technology appear adequate in scale to negate 1 km-diameter threat objects, and to pulverize 10 km-scale threat objects. No contemporary technical means of any kind appear capable of directly dispersing the ~100 km diameter scale Charon*-class cometary objects recently observed in the outer solar system, although such objects may be deflected to defensively useful extents. Exploitation of means discussed herein will apparently permit sub-kilometer-diameter near-Earth objects to be steered into the path of such giant threat objects, with dispersive pulverization likely resulting.*

Means of implementing defenses of each of these types are proposed for specificity, and areas for optimization noted. The primary challenges posed to defensive system designers are understanding the basic structure of the threat object, forestalling unwanted interactions when several nuclear explosions are used, and performing moderately high-precision delivery of adequate quantities of engineered mass into the vicinity of distant, rapidly moving objects. Rising to these challenges appears within the present-day capability of the international technical community.

Attention is invited to the prospects for rapid, economical implementation of initial active defenses, employing "Cold War surplus" military space hardware and systems, as well as to the indifference of a well-designed defensive system to highly detailed knowledge of the properties of a threat object. That cosmic threat objects present themselves with speeds greatly in excess of sound-speed is very useful in this respect, as material properties become of reduced interest.

Biospheric impacts of threat object debris are briefly considered, for bounding purposes. Under virtually every threat negation circumstance, these impacts are manageable.

Experiments are suggested on some of the myriad cometary and asteroidal objects of sub-kilometer diameter which pass by or through the Earth-Moon system every year in order to assess each of these defensive prospects, including means for diagnosing their results.

Introduction. The threat posed to the terrestrial biosphere from cosmic bombardment by comets and asteroids is peculiarly large in magnitude and low in frequency, relative to all the other threats known. In the current stage of solar system evolution, impact on Earth of objects sufficiently large to penetrate the atmosphere and crater its surface occurs with typical intervals of millennia. On time scales of several tens of millions of years, however, objects sufficiently large to profoundly impact the ability of the Earth's near-surface regions to support life have occurred in the past, and can be expected to occur in the future. Figure 1 indicates the relative dimensional and energy scales of Earth-impactors of various incident frequencies.

Since there are presently nearly 6 billion people on Earth, the statistical loss-of-life from such exceedingly rare events is nonetheless of the order of 100 lives lost each year, due to the biggest objects alone. The aggregate statistical loss-of-life due to the much more frequent impacts of considerably smaller-scale cosmic bombardments may be estimated to be several times the life-loss at the 'extinction level,' so that several hundred lives may be lost each year, on an actuarial basis. As human life is valued along the economic axis in the First World, this level of life-lost due to the immediate effects of cosmic bombardment has an imputed cost of the order of $1 B per year. (With purchasing power parity-based discounting to account for Second and Third World income scales and noting present populations in the First, Second and Third Worlds, the current value of this imputed cost due to cosmic bombardment is perhaps $0.3 B per year.)

A program of active defense against cosmic bombardment would be economically rational if it were to have a cost less than the time-averaged damage expectancy of cosmic bombardment. Other considerations than merely economic ones, such as insuring the survival of the human race, may justify somewhat higher expenditures. Some of the technical aspects of such a program to create and operate active defenses are outlined in the following.

<u>Character Of The Threat To The Biosphere From Comets And Asteroids.</u> As currently understood, the threat to terrestrial life arises from three aspects of cosmic bombardment: blast, heat and late-time atmospheric effects. Blast and thermal effects arising from the abrupt conversion of the kinetic energy of the incoming object into internal energy are well-understood, at least in principle, from the understanding of explosive phenomena in geophysical contexts which has developed over the past century. Due to the extraordinary physical scales of the larger impacting objects – not small compared to those of the Earth's crust and the scale-height of its atmosphere – the grossly non-spherical character of the blast waves and the comparatively localized nature of the thermal pulse may be somewhat non-intuitive, but nonetheless may be readily and reliably modeled computationally.

Atmospheric effects, in contrast, are significantly less well-understood, due to the complexity of solar-modulated atmospheric physics and chemistry, hydrometeorology and land-ocean interactions. Rather gross changes in atmospheric composition due to both direct and secondary injection of mass by incoming objects (and sets of objects) have been suggested to be important, and large, albeit transient, changes in the radiative transport properties by relatively modest amounts of micron-scale particulate mass have also been implicated in profound biospheric impacts.

Defensive systems must consider appropriately these latter effects. Primary defenses which would allow pulverized threat object mass in >100 megatonne quantities – corresponding to incoming objects initially well under 1 km in diameter – to impact the terrestrial atmosphere (and thus particulate-load the stratosphere) might inadvertently induce several kelvin global-average temperature drops. This would be an order-of-magnitude scale-up of the recent Mt. Pinatubo global cooling phenomenon, which is variously estimated to have injected ~20 megatonnes of largely sulphate particulate into the stratosphere and thereby to have induced a peak temperature drop of 0.4 – 0.6 kelvin. Moreover, fine particulate loading of the stratosphere may persist for a few years. Such temperature decreases may be sufficiently long in duration and large in magnitude to induce large-scale failures of agricultural production, with resulting widespread famine.

Threat Objects. Three major classes of threat objects may be delineated, based on composition. These are the cometary ones, composed predominantly of water and ammonia ices with embedded light-metal-oxide-based particulates, the stony asteroids composed of similar metal oxide particulates with varying degrees of compaction, and the nickel-irons composed predominantly of the metallic forms of the iron-group elements. Some of the properties of these objects pertinent to active defense are summarized in Figure 2.

Viewed from a threat negation perspective, the stony asteroids may actually be grouped into two major sub-classes, one consisting of "flying rubble piles" and likely representing cometary objects from which the volatile ices have been evaporated by long-term residence in the inner solar system, and the other consisting of highly compacted rock-like objects which likely originated by collisional fragmentation from larger "parent" bodies in the Asteroid Belt. These two sub-classes may be expected to vary substantially in the specific energy required to pulverize them (and also in their susceptibility to deflection-based defensive schemes).

Each of these classes of threat objects may also be categorized from a high-level defensive system architectural perspective, depending on their size. For each type of threat object, as will be seen below, there will be a maximum size which can be negated with non-nuclear explosive-based means. Objects of greater size can be negated along the pulverization and vaporization means of present interest only by use of relatively high-energy nuclear explosives.

Threat Negation Prospects In The Next Quarter-Century. The prospects for negating cosmic bombardment threats to the terrestrial biosphere during the next quarter-century necessarily are dependent for their implementing means on contemporary technology. As will be discussed further in the following, these appear to be readily sufficient to deal with 0.1 km-diameter threats by a variety of means, to cope with 1 km-scale threat objects with a much more limited set of tools, and to deal with 10 km-diameter threats only with rather heroic endeavors. These large differences in means of course derive immediately from the factor-of-

1000 in mass which separates each of these three size-classes of threat objects from its nearest neighbor.

At present, it is feasible to contemplate deflection, pulverization-with-dispersion and vaporization of threat objects as the primary defensive means – obviously supplemented by combinations of these. Deflection implies minimal energy expenditure and the longest warning-times. It thus admits of the greatest elegance and the widest variety of technical approaches, for it requires relatively very modest expenditures of energy, as it employs large time intervals as a very long lever on the planetary defense problem. Deflection-based defensive approaches also generally require unusually great knowledge of the threat object, e.g., precision and accuracy of data with respect to its orbit, its composition, its physical state and mechanical strength. Some pertinent energy scales are indicated in Figure 3.

Pulverization represents active defense conducted with an intermediate level of knowledge, and with relatively modest warning-times. In principle, it is very energy-economical, in that it proposes to break only perhaps at most one-billionth of the chemical bonds present in the threat object in the process of reducing it into meter-scale fragments. (In practice, the inefficiencies almost inevitably attendant upon even such coarse-scale pulverization are likely to degrade such excellent theoretical energy efficiencies by several orders of magnitude, particularly when the pulverization is rapidly performed, e.g. by explosive fracturing rather than fracturing in an adiabatically-operated press.) In addition, the resulting fragments generally must be given kinetic energies larger than their gravitational binding energies, in order to disperse the fragmented threat object and to force the fragments to interact with the Earth's atmosphere in an individual, non-collective manner – if they impinge on the atmosphere at all. Finally, if the time-interval before Earth-impact is small and the object is large, minimizing the total threat object mass incident on the Earth's atmosphere – both for peak localized thermal pulse and stratospheric particulate-loading considerations – requires that the fragments be given sufficient speed relative to their center-of-mass to separate them by a substantial multiple of the ~13 megameter Earth-diameter within whatever time-to-go is available.

Vaporization is the maximally robust defensive mode currently feasible to consider, and also is the most energy-intensive. Vaporizing objects of more that ~10^6 tonnes, i.e., of ≥100 meters diameter, by optimal conversion of their kinetic energy to internal forms is a daunting technical challenge to the defense at current technological levels. (Threat objects carry at most three orders of magnitude more specific kinetic energy than their own heat of vaporization, and delivering more than 500 tonnes of equipment to the immediate vicinity of a threat object doesn't appear feasible in the reasonably foreseeable future, as noted below.) For vaporization-based defenses against larger threat objects, nuclear energy sources are seemingly required. As will be discussed below, these means suffice to vaporize the 1 km-diameter objects which are believed to Earth-strike roughly every megayear. They are quite insufficient (with present rocket-based delivery means) to vaporize the ~10 km-diameter objects which strike every ~60 megayears – though they can robustly pulverize them. They cannot even reliably pulverize the *Charon*-class (≥100 km diameter) comets recently observed in the outer solar system.

Threat Pulverization. When pulverizing an incoming object whose kinetic energy is very large compared to the energy required to vaporize it, the quantity to be optimized – i.e., minimized – is the implementing mass; there is energy to spare. Since threat objects will always arrive at the Earth with speeds exceeding the 11 km/sec speed of Earth-escape – and typically with speeds of 20-60 km/sec, the defensive system designer is allowed to focus almost exclusively on minimizing the mass of pulverization equipment which must be transported to the immediate vicinity of the object.

Fragmenting a solid threat object into pieces of pre-specified maximum scale – e.g., 1 meter boulders, in the case of a well-consolidated stony asteroid – necessitates the imposition of a fracturing-level stress-field having the same periodicity. Indeed, in order to maximize the fragmentation benefits of large-scale crack propagation, it is desirable to simultaneously impose such a stress field over as large fraction of the object as may be technically feasible.

The technology-set conventionally employed for trenching and tunneling through high-strength rock seems applicable to this problem. Although emplacing a parallel sheet of periodically-spaced drill-holes, filling them with explosive and detonating the explosive strings synchronously in order to shear off a rock slab obviously is not practical for pulverization of cosmic threat objects, a technically-equivalent analog probably will be practical.

Specifically, a dense, refractory projectile with aspect ratio of 2–5 is capable of penetrating into hard rock to a depth an order-of-magnitude greater than its length, leaving in its wake a right circular cylinder of vaporized rock. The temperature and pressure in this cylindrical volume are comparable to that of detonated chemical high explosive – for whose creation the energy source is of course the kinetic energy of the incident projectile. This projectile is naturally slowly consumed as it traverses the hard rock. Its forward tip shocks the rocky medium into vapor, and ablates preferentially from its forward end and secondarily from its sides as the near-solid-density rock vapor flows over it. It is feasible to arrange its three-dimensional structure so that it "flies" stably through most all of its entire trajectory, i.e. so that the center-of-pressure integrated over its surface lies behind its center-of-mass until virtually all of the mass of the projectile has been ablated.

Linear strings of such penetrating projectiles, tip-to-tail-separated by 2–3 lengths, may be employed to create a "tube" of rock vapor of arbitrary length, and parallel linear penetrator strings may be used to generate sheets of such tubes. Obviously, these sheets may be expected to be functionally identical to sheets of blasting-holes used for deep-trenching through dikes of hard rock on Earth: the sheet-cracks connecting the plane-parallel tubes very soon after the tubes are formed will widen into fracture planes, and an extended slab of rock will then shear-off, either as a unit or as a set of boulders whose size is comparable to the spacing of the blasting-holes. If parallel sheets of penetrators are employed, an entire rock-mass may be rendered into slabs of rock or, more likely, a three-dimensional lattice of rubble. These sheets of dense, refractor hypervelocity penetrators – "tungsten knives" –

thus may be expected to serve to swiftly slice an asteroidal mass of any material into "bite size" chunks. See Figure 4.

As will be justified below, the nearest-neighbor distance of the penetrators in this sheet-lattice will need to be of the order of one meter. The sheets must be spaced so that the rubble from the N^{th} sheet's pulverization action has left the vicinity of the threat object's surface before the $(N+1)^{st}$ sheet arrives. This isn't a significant limitation, as pulverization will generally not be employed as a defensive option unless there is at least one megasecond time-to-go until Earth-strike; the time-spacing between sheets of penetrating-and-pulverizing projectiles can then be $10^2 - 10^3$ seconds, accommodating adequate dispersal between pulverizing events even if the rubble leaves the threat-object's surface at speeds as slow as 10 – 1 meter/sec. The use of as many as 10^3 penetrator-sheets is then reasonable.

Trading off against the inconvenience of needing many projectile-sheets is the ability to orient the sheets – and to maintain this orientation from the time of release to the time of impact – by simply imparting an appropriate vector angular momentum to a canister containing a tightly-packed "net" of hypervelocity penetrators. The projectile-sheet thus will impact the threat object in just the desired orientation. This approach admits of an especially simple – and thus highly reliable – deployment mechanism, one moreover well-adapted to existing ICBM post-boost vehicles. See Figure 5.

Going from two to three dimensions, equi-spaced stacks of such sheets of projectile strings may be erected in space to form a lattice which, when made to collide with a threat object of comparable dimensions, may hypersonically penetrate it through its entire thickness with blasting holes of meter-spacing – and thus render it into a rubble-pile of meter-scale boulders, interpenetrated with tubes of rock vapor of density $\sim 10^{-1} - 10^{-2}$ that of solid density, which will serve to swiftly disperse it. Such extended lattices are of limited utility unless the velocity vector of the lattice is reasonably well-aligned with that of the threat-object at which it is directed; however, the required degree of co-alignment is straightforward to arrange with modern equipment.

In vacuum, no impediment exists to the erection of such projectile assemblies– and, in particular, there is an abundance of time available for reasonably high-precision lattice generation from a stowed-for-transport package.

A complication which must be dealt with in a robust manner during pulverization is the possible premature dispersal of a "flying rubble pile" of moderate (e.g., 1 km diameter) scale. Such a pile may harbor a large number of, e.g., 100 meter-scale consolidated objects easily capable of penetrating to the Earth's surface, and yet may aggregate these objects only very weakly, via gravitational binding. If not pulverized carefully, such a rubble pile may disassemble early in the pulverization process into an awkwardly large family of mini-threat objects, under the influence of the energy inadvertently "leaking" from the pulverization working-site into the remainder of the "parent" threat object, during the early phases of pulverization. Alternatively, a weakly aggregated threat object of very low mechanical strength may spontaneously disassemble as it comes within the terrestrial Roche limit, due to tidal forces – as Shoemaker-Levy 9 did prior to its final plunge into Jupiter –

although the smallness of the terrestrial Roche limit probably obviates such concerns except for near-grazing-incidence rubble-piles.

Pulverization employing a massive three-dimensional penetrator lattice, demonstrated and validated in "practice sessions," may be the preferred approach to such a complication, as it definitively pulverizes a threat object, including a flying rubble-pile, before it can possibly disassemble – or move in any other fashion. An alternative approach applicable to larger threat objects which may be difficult to pulverize with a 3-D lattice of feasible size is to employ a sequence of lattice-sheets of penetrators to disassemble the flying rubble pile and then to pulverize-at-discretion any unacceptably large objects within it which remain on Earth-collision trajectories.

Figure 6 illustrates the use of hypervelocity penetrators for both pulverization and vaporization of threat objects; it presents results from both computational and experimental studies of pertinent hypervelocity penetrators interacting with high-strength plastic, cement and steel targets (which may be taken as surrogates for very strong ice or carbonaceous chrondritic, stony and nickel-iron threat objects, respectively). The computer simulation studies were performed by our able colleague Yu-Li Pan, using sophisticated, first-principles physics design codes which model elastoplastic hydrodynamics and all pertinent types of energy transport; these codes are known to be high-fidelity models of physical reality from detailed comparisons with a wealth of well-diagnosed pertinent experiments.

Figure 6A indicates initial conditions for a set of studies employing a long tungsten hypervelocity penetrator interacting with a steel target, while Figures 6B and 6C show "snapshots" in time of the interaction for an incident penetrator speed of 4.5 km/sec, where the unit compression (i.e., normal density) contours of the tungsten and the steel are shown. Figure 6D displays final bore-hole or cavity contours for identical projectiles of varying incident speed, and notes that energy conservation is expressed by linear cavity volume increase with incident kinetic energy. Figure 6E notes that usage of penetrator mass is optimized by using small (length-to-diameter) aspect-ratio penetrators, a point which is generalized somewhat in Figure 6F; "P/L" expresses the dimensionless ratio of the penetration depth in the material being studied to the initial length of the penetrator. Figure 6G indicates the hypervelocity penetrator system configuration suggested by many such studies: a heel-to-toe sequence of small aspect-ratio penetrators is best for deeply penetrating any solid. Figure 6H indicates how a single such penetrator interacts with concrete as a function of initial penetrator speed; little improvement is seen for incident penetrator speeds above that sufficient to largely vaporize the concrete. Figure 6I indicates how a short string" of 3 such penetrators in a geometry similar to that indicated in Figure 6G interacts with a concrete target, immediately after the third projectile has completely ablated; some late-time target relaxation has yet to occur near the tip of the bore-hole. Figure 6J indicates how a single steel sphere of 1 cm-diameter and incident speed of 5 km/sec penetrates on-axis into a strong plastic cylindrical target, while Figure 6K indicates how an identical target evolves when 3 successive spheres are made to impinge in succession on the same axial location; the penetration depth into the target is seen to be approximately 3 times that of the target struck by only a single penetrator. Finally, Figures 6L and 6M indicate the same phenomena in two concrete targets struck by a single steel sphere and by 3 steel spheres in succession, respectively (these two targets fragmented more severely than did the pair of plastic ones, for well-understood reasons). In these experiments, measured bore-hole total depths and radii-vs.-depth agreed with prior physics code predictions to better than 10% accuracy, as much prior experience had indicated they would.

We therefore are highly confident that our modeling-code based predictions provide a very reliable basis for evaluating active defense concepts on much larger scales, for physics is scale-invariant and predictions of these codes have been extremely extensively examined and validated in very many pertinent experiments.

Threat Vaporization. Vaporization of a threat object of course represents one end of the spectrum of negation robustness, as well as another on the spectrum of energy (and mass) cost-of-negation. Thus, it is the method-of-choice for an ultimate defensive layer, or when large amounts of energy are readily available. Because of the huge mismatch in sound-speeds of a nuclear explosion-generated fireball consisting only of the explosive debris and of ordinary zero-temperature matter, coupling of nuclear explosive energy to essentially any kind of threat object is highly inefficient, if the energy is released on or above the object's surface.

One may optimize this coupling efficiency by embedding the explosive sufficiently deeply in the threat object prior to energy generation so that the ensuing shock emerges nearly simultaneously at virtually all points on the object's surface, i.e., one may generate the explosion's energy in the object's core. If the surface-emergent shock from such a well-placed explosion generates a post-shock temperature above the local critical temperature, this is sufficient to assure that the entire object will be vaporized; if the emergent shock strength is above the Young's modulus of the object material, this is sufficient to guarantee that the entire object will be pulverized. Straightforward arithmetic indicates that of the order of 1 gigaton of energy deposited in the core of a 1 km-diameter object will suffice to vaporize it (after all, its mass is of the order of 1 gigatonne). The same energy pulse placed at the core of a 10 km-diameter object will generate ≥0.1 kilobar stress levels when it reflects from the object's surface, sufficient to pulverize it, except when it is composed predominantly of unfractured nickel-iron (in which case order-of-magnitude higher stress-levels may be required, those which could be attained on the surface of a ~5 km-diameter object).

Detailed computer-based physical simulations, supplemented with pertinent testing of military nuclear explosives systems, suggests that emplacing a large nuclear explosive in the center of a multi-km-diameter consolidated object may be feasible in the circumstances of interest. The same basic approach as was pursued for non-nuclear pulverization is employed, with a string of megaton-scale nuclear explosives substituting for the string of dense, refractory projectiles. (This procedure is in part based on experience with nuclear explosives. The proposed geometry is novel in its spatial extent, and possible interactions are complex and of high energy-density. Nonetheless, we consider the success of the proposed procedure probable but by no means assured. Experimental validation of detailed computer modeling results clearly is required.)

Each nuclear explosive, wrapped in a suitable structure of high-strength thermal insulation, advances kinematically to the current end of the advancing bore-hole, comes to a stop in the manner of an earth-penetrating munition, immediately deposits its energy-pulse, and thereby extends the ≥100 meter diameter bore-hole in the object radially inward by another ~100 meters (after a radial hydrodynamic relaxation interval of ~0.1 second after each pulse. The exceptionally high speeds of the incoming nuclear charges makes it probable that charge emplacement will occur when-and-as expected, even though the final charges must traverse possibly several kilometers of still-rarefying and reasonably hot rock vapor (which long, reasonably dense tube of vapor serves to decouple usefully many of the prompt effects of the leading charge from all of its followers). Ablative insulation with a net transport time-constant as modest as 1 second will suffice to completely decouple the arriving charge from ambient thermal conditions, and an adequately high-strength mechanical support for this thermal decoupling layer may be provided for. Acceleration-switched fusing will automatically generate the nuclear energy pulse when the charge embeds itself in the innermost tip of the bore-hole being drilled, and standard kinematic decoupling approaches, extended to the order-of-magnitude higher speeds of impact of present interest, may be used to provide for proper operation of the charge. None of these techniques are completely novel, and their fundamentals "are known to one ordinarily skilled in the art." (As also noted above, the unusual physical conditions make it highly desirable to validate these approaches experimentally, well before the time of real defensive need.) See Figure 7.

The drilling of a bore-hole of ~0.1 km minimum diameter to the center of even a 10 km-diameter threat object can be performed on a time-scale of the order of 5 seconds, and its character assured in advance by giving the appropriate set of reasonably precise initial positions and velocities to a set of a few dozen identical nuclear charges of types which presently exist in abundance (e.g., the several thousand warheads of the SS-18D ICBM, now commencing decommissioning under START II). The repeatedly demonstrated performance of modern post-boost vehicles in positioning remarkably precisely reentry vehicles in linear coordinate-linear momentum-angular momentum phase space is more-than-adequate for this task.

Immediately after the bore-hole to the center of the threat object is completed, it is appropriate to emplace the main charge, whose function it is to initiate a radially diverging shock of maximum feasible strength. Single space-launches using the largest boosters presently available, i.e., *Energiya*, can emplace gigaton-scale nuclear charges anywhere in the inner solar system between the orbits of Mars and Venus, and the use of such an explosive is contemplated for dispersing the largest threat objects. The relatively high-strength shock which can be engendered by a charge of this scale will overtake the comparatively weak shocks launched by the bore-hole drilling operation well before the cumulative effect of all of them have significantly displaced outward the surface of the object, so that this final strong shock will "see" virtually all of the object in nearly undisturbed condition. Then, as noted above, this shock will heat and stress the object's surface (and, to even greater extents, all of its interior mass) to extents readily estimated from basic mass and energy considerations, i.e., 1 km-scale objects will be completely vaporized, and 10 km-scale objects will be reliably pulverized and then dispersed with ~0.1 km/sec mean speeds, relative to the center-of-mass of the threat object. (Even as soon as ten days later, the diameter of a 10 km-diameter object's debris cloud will be a dozen times that of the Earth.)

Such an approach could also be employed to deflect a giant, *Charon*-class comet, if such an object were detected with sufficient time-to-go in its Earth collision-bound trajectory. The main charge, dynamically emplaced and detonated at a depth of the order of 10 km into the comet's surface, would blast a crater of a few tens of km diameter in its side. The crater ejecta, heaved with a typical speed of ~0.03 km/sec, would mostly escape, since the escape velocity from the surface of a 100 km-diameter comet is ~25 meters/sec. (For this reason, no mass would be lost from elsewhere on the comet, no matter how mechanically weak it might be, when the shock reflected off other portions of its surface, distant from the crater.) The giant comet, having thus lost $\sim10^{-2}$ of its mass in escaped crater ejecta, would perforce undergo a velocity change of $(\sim10^{-2})$(0.03 km/sec), or ~0.3 meters/sec. If this maneuver were performed with a time-to-go as small as 1 year, when the comet might be expected to be inside the orbit of Jupiter, it could shift the Earth-comet collision parameter by $\sim10^4$ km, just sufficient to change a direct hit into a near-miss.

If such giant cometary objects can be detected with significantly greater time-to-go, it might be feasible to steer into its path an asteroid of at least several km diameter from the main Belt. The resulting collision at ≥25 km/sec, occurring as the giant comet crossed the Belt, would certainly pulverize and likely vaporize both asteroid and comet. This conceptually interesting prospect twice-leverages anthropogenic mass, in that a relatively very modest amount of equipment is employed to explosively deflect a carefully selected natural object by perhaps 1% of its orbital velocity, sufficient to steer it into the path of the sunward-falling comet. This steered asteroid mass then acts to convert a sufficiently large fraction of the comet's kinetic energy into internal forms to negate it completely as a threat. The energetics of this approach appear attainable with existing equipment, but its overall feasibility cannot be assessed until a significantly more definitive census of the smaller objects in the Belt is obtained – presumably with space-based observational means.

Less spectulatively in both required implementing mass and Main Belt population statistics is the prospect of employing the "best" of the class of $\sim10^6$ near-Earth objects with diameters of ~100 meters whose existence has only very recently been discovered. A short sequence of steering-events, each one of which involves ~1 tonne of anthropogenic mass employed to ablate $\leq10^3$ times greater mass from the $\sim10^6$ tonne near-Earth object, could readily impart the precise velocity change (of the order of 1 cm/second in magnitude) sufficient to steer the "best of class" into the path of the incoming giant threat object. The center-of-mass kinetic energy would not be greatly in excess of 100 megatons, but the mass ejected from the resulting impact crater on the giant threat object is likely to carry off enough momentum to convert a direct hit on the Earth into a near-miss. Thus, employing twice the high specific kinetic energy (relative to both sound speeds and threat-object escape speeds) of objects in solar orbit makes feasible-in-principle defense of the Earth from impact by even giant threat objects – moreover with means not requiring use of nuclear explosives.

Threat Negation Equipments. Threat negation of all the types considered here involves the placement of mass in the immediate vicinity of the threat object (or set of threat objects). Depending on the particular defensive approach taken to negation, this mass may be in the form of thousands of small hypervelocity projectiles or 1 – 2 dozen nuclear explosives. In either case, precision positioning of the defensive mass relative to the threat object is likely essential to success of the defensive mission. Figure 8 summarizes the approaches to active defense from an energetics standpoint, which in turn motivates defensive system mass budgets.

Fortunately, means are presently available in quantity for these placement tasks, all of which must be executed far from Earth, as noted both above and below. A few examples may serve to illustrate this. The SS-18 ICBMs of the former Soviet Union, of which more than 300 still remain but are scheduled for retirement prior to 2003 under START II, are each capable of sending a payload of roughly 2 tonnes into Earth-escape trajectory (with a modern solid rocket motor replacing their current PBV propulsion). The post-boost vehicles (PBVs) of both Russian and American MIRVed ICBMs are all scheduled for retirement under START II. The best of these are capable of deploying typically 10 objects, each of 0.1-1 tonne mass, into quite distinct trajectories with velocity precisions of the order of 1 part in 10^5 and orientation precisions of the order of 1 part in 10^3 (which orientations are maintained by appropriate angular momentum endowments imparted to the objects as they are deployed). These already-demonstrated precisions are substantially better than are likely to be required to position kinetic energy penetrator-nets and nuclear explosives relative to threat objects, in order to attain optimum defensive results: e.g., they correspond to threat-negation packet placement-precision of <0.1 km across a distance of 10^4 km.

High-precision laser radars and inertial frame-generating units, both stellar and internal, exist which are adequate to support such precision positioning of negation packets in the deep space environment. For example, the imaging laser radar carried on the *Clementine* spacecraft which performed the first high-resolution, three-dimensional mapping of the entire Moon just last year demonstrated a ranging precision of 10 meters across a 0.64 megameter range, limited only by the counting-precision of its 16-bit clock; its demonstrated performance capabilities would have supported ranging to a few meters precision at distances in excess of one megameter. The camera of *Clementine's* imaging laser radar has since been upgraded to a 5 μradian resolution level. Thus, with a few obvious, easily implemented enhancements, the *Clementine* imaging laser radar module could perform 1 part in 10^5 precision range <u>and</u> angular position measurements of threat objects at rates as high as 10 Hz, over multi-megameter distances. Similarly, either of the two independent laser-based inertial measurement units carried by *Clementine*, together with either of its two independent stellar inertial reference units, would be entirely adequate, in bias, noise, drift, dynamic range and bandwidth, to guide the threat negation platform throughout its threat object-negation packet-dispensing program. Some of these *Clementine* technologies are shown in Figures 9A and 9B, in as-flown configuration.

To support vaporization of 1 km-diameter threat objects and definitive dispersion of 10 km-diameter objects, very large amounts of energy will be required, of the order of a billion tonnes of TNT-equivalent (noting that a 1-km comet has a mass of ~0.5

billion tonnes and a heat-of-vaporization of ~0.3 billion tonnes of TNT-equivalent). While the efficiency of the best nuclear explosives is high, it is amusing to note that it amounts only to $\sim 10^{-3}$ of the rest-mass energy of the explosive. Fortunately, at least one very high-capacity space launch system is presently available, the Russian *Energiya*, which can put ~25 tonnes of payload into an Earth-escape trajectory (topped with a suitable – and presently available – upper stage). Such payload mass is sufficient to deliver a single integrated nuclear explosive of the required energy production capability to vaporize km-scale threat objects and to disruptively pulverize 10 km-diameter ones, via the high-efficiency "from the inside out" technique discussed above.

It is a fortuitous consequence of the end of the Cold War that all of these equipments – created at aggregate costs far in excess of $100 billion – are currently available at essentially zero cost, as "war surplus." They can potentially be employed to comprise the essential hardware infrastructure of a highly capable active defense of the terrestrial biosphere against cosmic bombardment, quickly and inexpensively.

Mass Budgets For Threat Negation. The total quantities of mass required to be emplaced with reasonable precision in the vicinity of incoming threat objects range from the modest to the demanding, depending on the choice of threat negation technology to be employed. Fairly careful reckoning of mass budgets, in turn, indexes the likely cost of active defense systems in the near-term, for space-launch costs seem likely to dominate at least the "hardware" portions of defensive systems budgets. It seems especially important to give the highest priority consideration to systems whose space-launch mass budgets do not exceed those which can be satisfied by the "Cold War surplus" hardware inventories of the U.S. and the former Soviet Republics becoming available under START II – for these are the systems which will be by far the most economically feasible to implement or employ in the foreseeable future.

For nuclear explosive-based defenses, perhaps 50 charges of 1 megaton-scale would be sufficient to drill into the core of even a 10 km-diameter threat object. (Of course, far more modest means would suffice to negate a 1 km-diameter object, and significantly smaller threat objects may be dealt with by entirely non-nuclear means.) Perhaps two such charges and a modest amount of post-boost vehicle, with aggregate mass under 2 tonnes, could be thrown into an Earth-escape trajectory by a SS-18 ICBM topped with a suitable, high-I_{sp} upper stage. A single gigaton-class charge could be similarly launched on a single *Energiya* booster, equipped with a *Centaur*-class upper stage. Approximately two dozen SS-18s and a single *Energiya* would thus suffice to execute the launch portion of the largest presently foreseeable active defensive operation.

In a hybrid defensive scheme, one face of a threat object could be pulverized with a barrage of hypervelocity penetrators and then vaporized, with the use of a nuclear explosive standing off of the order of one radius from the expanding rubble. The resulting shock wave may give the remaining threat object a relatively gentle and sustained acceleration, and thus a reliable deflection from its previously Earth-bound trajectory.

The mass-multiplication efficiency of the most mass-efficient non-nuclear threat dispersion schemes known to us – those involving hypervelocity projectile-based conversion of threat object kinetic energy to internal energy with unit efficiency – depends on the square of a threat object's speed in the Earth reference frame (which is its specific kinetic energy), in units of its zero-temperature adiabatic sound-speed (which squared quantity we use to estimate the object's specific heat-of-vaporization). These efficiencies range from $\sim 10^2$ for vaporization of the lowest-speed nickel-iron asteroids to $\sim 10^6$ for pulverization-and-dispersion of heliocentric retrograde-orbiting ice-rich comets.

For defenses not using nuclear explosives, the size – specifically, the mass – of the threat object which can be successfully negated, either by pulverization or vaporization, scales linearly with amount of mass available to direct upon it as hypervelocity projectiles. The total mass which all launchers becoming available under START II could put into Earth-escape trajectory is between 300 and 500 tonnes. An upper-bound mass-multiplication efficiency of 10^6, corresponding to pulverization of a very high-speed threat object, would thus permit a single half-gigaton object – a comet or a stony asteroid of ≤1 km-diameter – to be negated by impact of hypervelocity penetrators, if the entire START II-generated launch capacity were to be expended in transporting arrays of such penetrators.

Figure 10 gives estimates of the size of objects of various compositions and orbital characteristics which can be negated with the various active defensive technologies , both non-nuclear and nuclear, which we have discussed, for two types of approaches to system deployment: single, heavy-lift launch and launch on a fleet-of-100 SS-18s with high I_{sp} upper-stages. The mass efficiency – the mass of the threat-object negated per unit mass of defensive equipments lofted into interplanetary space – is indicated for each of the four major approaches as E_{mass}. It is clear both that non-nuclear active defenses will suffice for the smaller threat objects which Earth-strike relatively frequently, and that only nuclear defensive means are adequate for the sizes of threat objects which threaten life on continental and all-Earth geographical scales and which are apt to strike the Earth no more frequently than once every million years.

Biospheric Consequences Of Threat Negation. In order to minimize the biospheric consequences of threat negation, it is necessary to ensure that mass and energy loadings of the Earth's atmosphere be kept below reasonably well-understood damage thresholds, in the worst case contingency, and that possible atmospheric composition changes and particulate loadings be managed very conservatively (because of greater present-day uncertainties regarding the consequences of such changes).

Mass and energy loadings of the atmosphere and the underlying surface of the Earth are of course related principally through the speed, composition and mechanical state of the residual debris of the post-negation threat object. It is required that thermal and acoustic loadings on the ground be below tolerable limits at the most threatened location(s), under the worst contingency. The corresponding energy releases in the atmosphere as a function of height and thus of debris size, composition and mechanical state, are very well-understood in principle at the present time, due to the extensive studies of the past several decades on military applications of nuclear explosives, in the atmosphere and near the Earth's surface.

The general requirements are to keep peak overpressures below ~1 psi and peak thermal pulses below ~0.5 calorie/cm^2/minute and below ~1 calorie/cm^2 time-integrated for intervals of ~5 minutes or less, in order that there be no significant damage to people, structures or crops, under worst-case conditions. (Crops are probably the most sensitive, particularly during intervals of peak insolation in local summer, when they are already thermally stressed.) These requirement may be met by ensuring that no more than ~10 kilotons/km^2 of deeply penetrating debris-energy arrive at any location within the troposphere, e.g., that no more than ~100 tonnes/km^2 of threat object debris are incident (assuming a not atypical 30 km/sec atmospheric entry speed). This requirement is consistent with threat object pulverization with equipment designed to generate rubble of 1 meter scale, which ensures that debris objects as large as 10 meters in diameter will be exponentially rare. (One meter boulders will almost invariably disintegrate in the upper troposphere or even the lower stratosphere, while 10 meter ones may survive down to altitudes of a few kilometers and, if of unusually high strength-in-bulk, may even reach the ground.) If the projected cross-section of the Earth of ~10^8 km^2 were uniformly loaded at this level, 10^{10} tonnes of incident threat object rubble could be tolerated, from a blast and heat standpoint; this corresponds to a compact object of ~2 km diameter.

It is likely that particulate loading of the stratosphere poses a more stringent limit. Calculations, verified semi-quantitatively by observations over the past several years of the global effects of Mount Pinatubo's ejective loading of the stratosphere, suggest that stratospheric loadings of micron-scale particulate above ~100 megatonnes total mass will have sufficiently large global cooling effects for several years as to impair markedly a large fraction of agricultural activity in the sub-tropics. (Mount Pinatubo is estimated to have loaded the stratosphere with ~20 megatonnes of mostly sulfate particulates, most of them of eventual diameter of $\leq$1 μm.) Debris from pulverized comets and particularly fragile stony asteroids might load the stratosphere with fine particulate with moderately high mass-efficiency, e.g,. $\geq$10% of the incident mass could be retained in the stratosphere. It is therefore likely that, in order to reliably avoid the risk of an "asteroidal winter," the post-negation non-volatile debris allowed to impact the Earth's atmosphere will have to be upper-bounded at ~10^8 tonnes, that mass corresponding to a compact object of ~0.4 km diameter.

It appears highly unlikely that threat object dispersion would be done so gently or with so little time-to-go that debris mass of even this scale would impinge upon the atmosphere. The debris cloud resulting from the dispersal of a 1 km-diameter object would have to be virtually centered on the Earth and less than 4 Earth diameters in order to achieve this atmospheric loading. Such a compact cloud could be attained only if the product of time-to-go and mean dispersion speed were less than 25 megameters, e.g., if time-to-go was 10^6 seconds and mean dispersion speed were 25 meters/second. Both of these are improbably small.

Now, it is undeniable that even a highly effective defensive system may have non-zero "leakage" of objects sufficiently massive and mechanically strong to penetrate to the Earth's surface. Recalling that the Tunguska object was likely a stony asteroid of the order of 50 meters in diameter and the Barringer Crater in Arizona is attributed to a nickel-iron asteroid of perhaps 80 meters diameter, it is clear that leakage of a single 100 meter object escaping from the negation of a much larger one could result in millions of casualties.

It is therefore likely that defense-in-depth will be required of any system of active defense, and that defensive means which are robust even when time-to-go is minimal be deployed to undergird ones which are employed at earlier times and greater distances from Earth. If non-nuclear means constitute the outermost or first defensive layer, it will be necessary to withhold some space-launch capacity from this layer in order to have the necessary means to launch the under-layer. How much launch capacity must be reserved will obviously depend sensitively on the estimated mass and the number of "leakers" – and whether non-nuclear or nuclear means will be employed for leaker negation.

Needed Threat Objects Data, Defense-Validating Experiments And Diagnostics. Perhaps the most crucial single parameter needed at any time in the life-cycle of an active planetary defense system is the time-to-go before the first Earth-strike of an object having a diameter of more than a few dozen meters. While such objects and associated times-to-go may be catalogued with considerable accuracy during the next 1–2 decades for the near-Earth objects presently orbiting in the inner solar system without large changes from the present situation, the corresponding information for high-eccentricity asteroids, long-period comets, etc., seems likely to become available only with considerable, sustained effort of types which are not well-represented in current observational endeavors. It is the latter objects which may present the greatest threat to the terrestrial biosphere, for though they are more distant, they arrive with greater speed and – most importantly – far less warning; they are the threats which could be uniquely "first pass deadly." Near-Earth objects, in qualitative contrast, very likely will be seen for many orbital periods – i.e., many years – prior to possible Earth-strike, soon after reasonably capable sky surveillance becomes operational.

Of comparably fundamental importance in threat characterization are diagnostic means for remotely assessing the composition and, most particularly, the mechanical conditions of potential Earth-impactors. It seems likely that active defenses against "flying rubble piles" will be significantly easier to implement (and reliable to use) than ones against nickel-iron asteroids of the same mass, with highly consolidated stony asteroids being the intermediate case. The use of diagnostic spacecraft of the *Clementine* class to probe distant threat objects well in advance of their arrival in near-Earth space will permit economies in defensive system operation, making it unnecessary to regard every incoming object as a nickel-iron asteroids and to expend defensive resources to defeat such relatively formidable threats. Such modest-mass spacecraft will presumably be dispatched on very high-speed trajectories, in order to return results sufficiently early to support launch of the appropriate number and class of pulverization or vaporization equipments.

After such remote diagnostic means are demonstrated successfully in the program of defensive system development and testing, it will become of immediate interest to test various defensive systems and schemes in small scale. (Such sub-scale experiments are appropriate both to minimize per-event costs and to maximize the number of experimental opportunities in any time-interval.)

Fortunately, sub-scale experimentation, followed by performance evaluation and then by defensive system validation, seems eminently feasible, in view of the relatively huge population of sub-100-meter diameter objects which pass within the lunar orbit of the Earth each year. Since all such objects are gravitationally unbound (by large margins) relative to the Earth-Moon barycenter, dispersion of them with various defensive prototypes and system operating in sub-scale can have no possible adverse consequences – once they are "kinematically downwind" of the Earth.

Obviously, it will be crucial to diagnose fully the interaction of defensive equipments with these sub-scale proto-threat objects. Doing so will require both survivable remote sensing platforms and telemetry-intensive non-survivable ones which will fly immediately behind objects launched by defensive systems to pulverize or vaporize the proto-threat objects and which will provide the high-resolution data on pulverization and vaporization events required for knowledge-based certification of full-scale active defensive systems. Indeed, preliminary work has already been performed in the specification and design of platforms and equipment suitable for such purposes, in connection with follow-on asteroidal exploration missions of the *Clementine* mission-family. Detailed planning of defensive systems will greatly benefit from such experiments. Such planning should, therefore, be deferred until experimental results are available.

Manifestly, defensive system robustness can be fully demonstrated only with full-scale experiments. These will logically follow the sub-scale experiments, and, in order to be performed in a timely manner, will necessarily involve test objects found and worked with at locations substantially more distant from the Earth.

Conclusions. Active defense of the terrestrial biosphere from all likely scales and natures of cosmic bombardment can be commenced during the next quarter-century. Contemporary technology is sufficiently powerful to negate threat-objects of all kinds heading for the Earth with diameters $\leq$10 km, by either pulverization or vaporization for objects $\leq$1 km in diameter and by pulverization-and-fragment dispersion for multi-km diameter objects. Deflection of a giant threat object – with diameter ~100 km – may be feasible by using these pulverization and vaporization techniques to steer an optimally chosen sub-kilometer-diameter near-Earth object into its path.

Critical enabling hardware for initial implementation of both nuclear and non-nuclear defenses is currently becoming available as "Cold War surplus," in the form of heavy ICBMs and associated post-boost vehicles. These can place the required defensive equipments in the immediate vicinity of the incoming threat objects, with great cost-savings. Other equipments of the types demonstrated in the recent *Clementine* lunar mission will greatly facilitate inexpensive, near-term defensive system testing, as well as the required maximally distant detection, tracking and categorization of small objects.

Near-term experimentation on the many relatively small objects passing the Earth every year at closest approach distances of a few thousandths of an AU will suffice to characterize most of the key features of representative threat objects, as well as validating various near-term approaches to active defense of the terrestrial biosphere. Full-up, full-scale exercising of capabilities validated in sub-scale will then provide the necessary assurance that active defenses will perform robustly when required.

Acknowledgments. We thank Drs. Yu-Li Pan and John Hunter for use of their computational and experimental data regarding hypervelocity penetrator interaction with targets, Dr. William Tedeschi for helpful comments and data regarding the explosive fracture energetics of natural materials and Gordon Wenneker, Gloria Purpura, and Linda Scott for expert assistance in preparing this manuscript and its graphics.

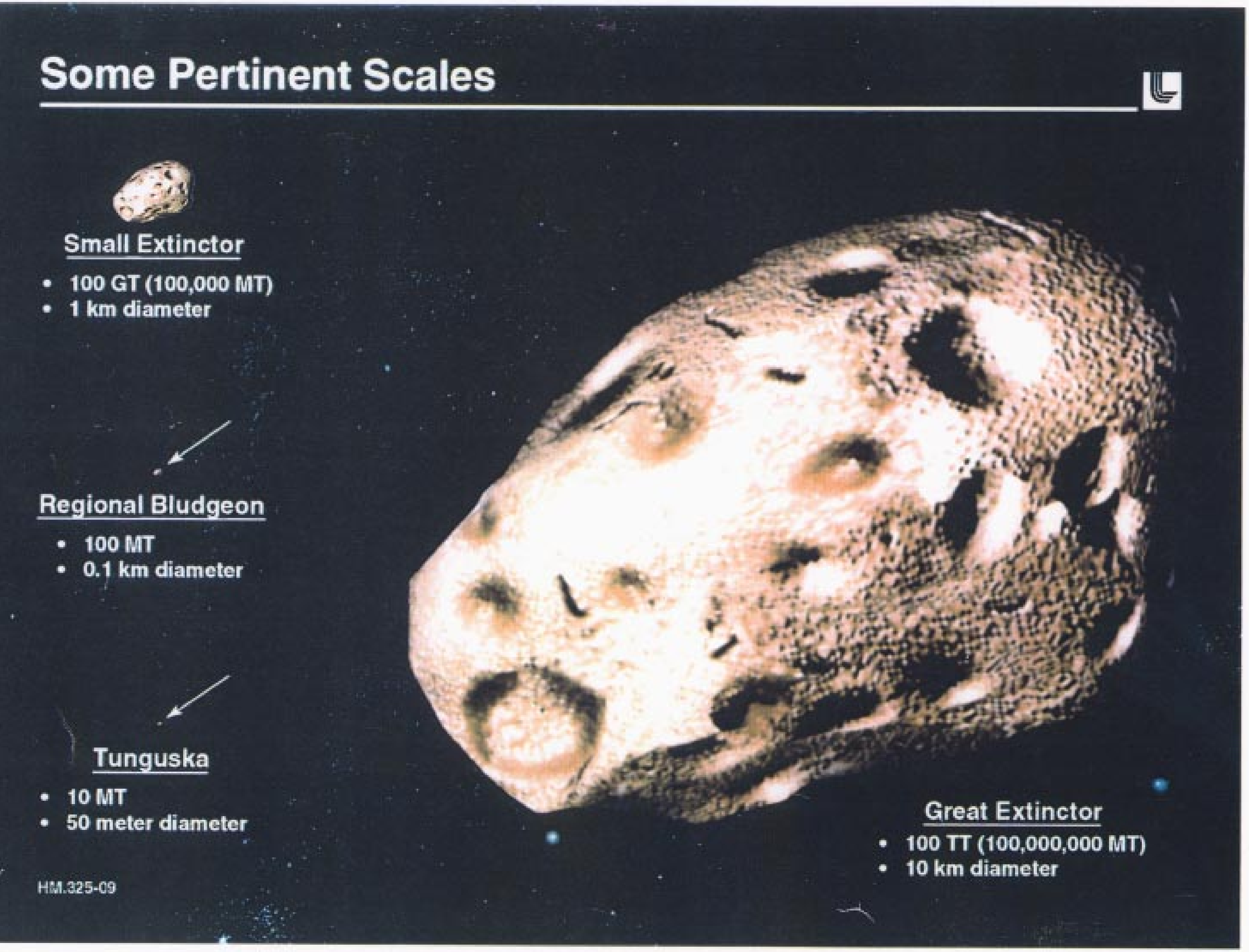

Some Pertinent Scales
Small Extinctor
• 100 GT (100,000 MT)
• 1 km diameter
Regional Bludgeon
• 100 MT
• 0.1 km diameter
Tunguska
• 10 MT
• 50 meter diameter
Great Extinctor
• 100 TT (100,000,000 MT)
• 10 km diameter
HM.325-09

Figure 1

THREAT OBJECTS

	Comets	Stony/Carbonaceous Asteroids	Metallic Asteroids
Composition:	Ice & Rocks	Rocks	Ni–Fe Metals
Strength:	Weak	Weak <–> Moderate	Strong
Relative Flux:	5%	85%	10%
Relative Energy:	4	1	1
Threat Nature:	Unpredictable	Predictable	Predictable
Warning Time:	Months –> Year	Years –> Decade	Years –> Decade

50517-RAH-02

Figure 2

SPECIFIC ENERGY SCALES OF COSMIC BOMBLETS

$10^{-5} - 10^{-2}$	$\ll$	$10 - 10^{2}$	$\ll$	10^{3}	$\ll$	$10^{5} - 10^{6}$	Joules/gram
Gravitational Binding Energy (0.03 – 10 km dia.)		Pulverization Energy		Vaporization Energy		Kinetic Energy (Earth–Frame)	

50511-LLW-05

Figure 3

THREAT OBJECT PULVERIZATION

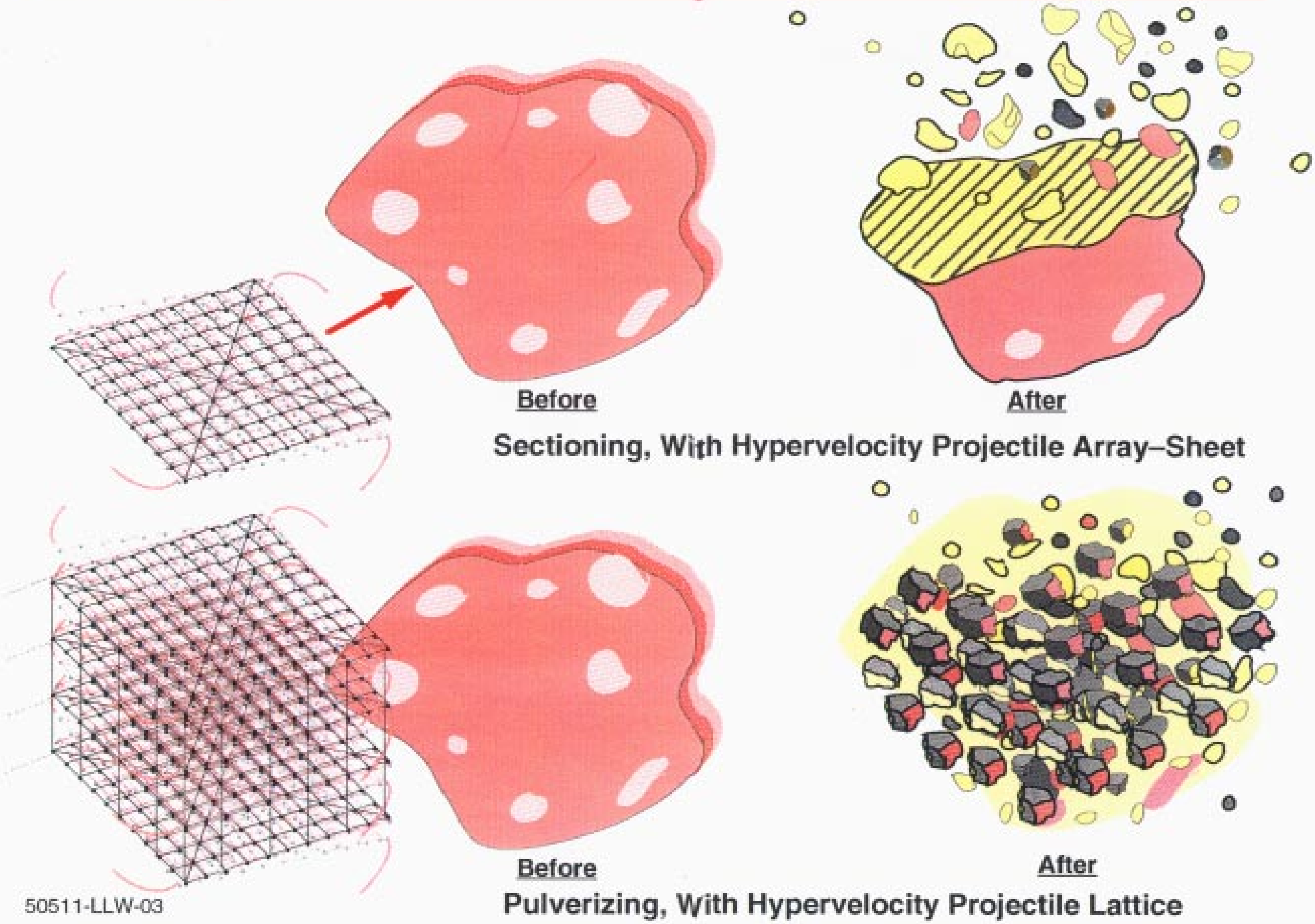
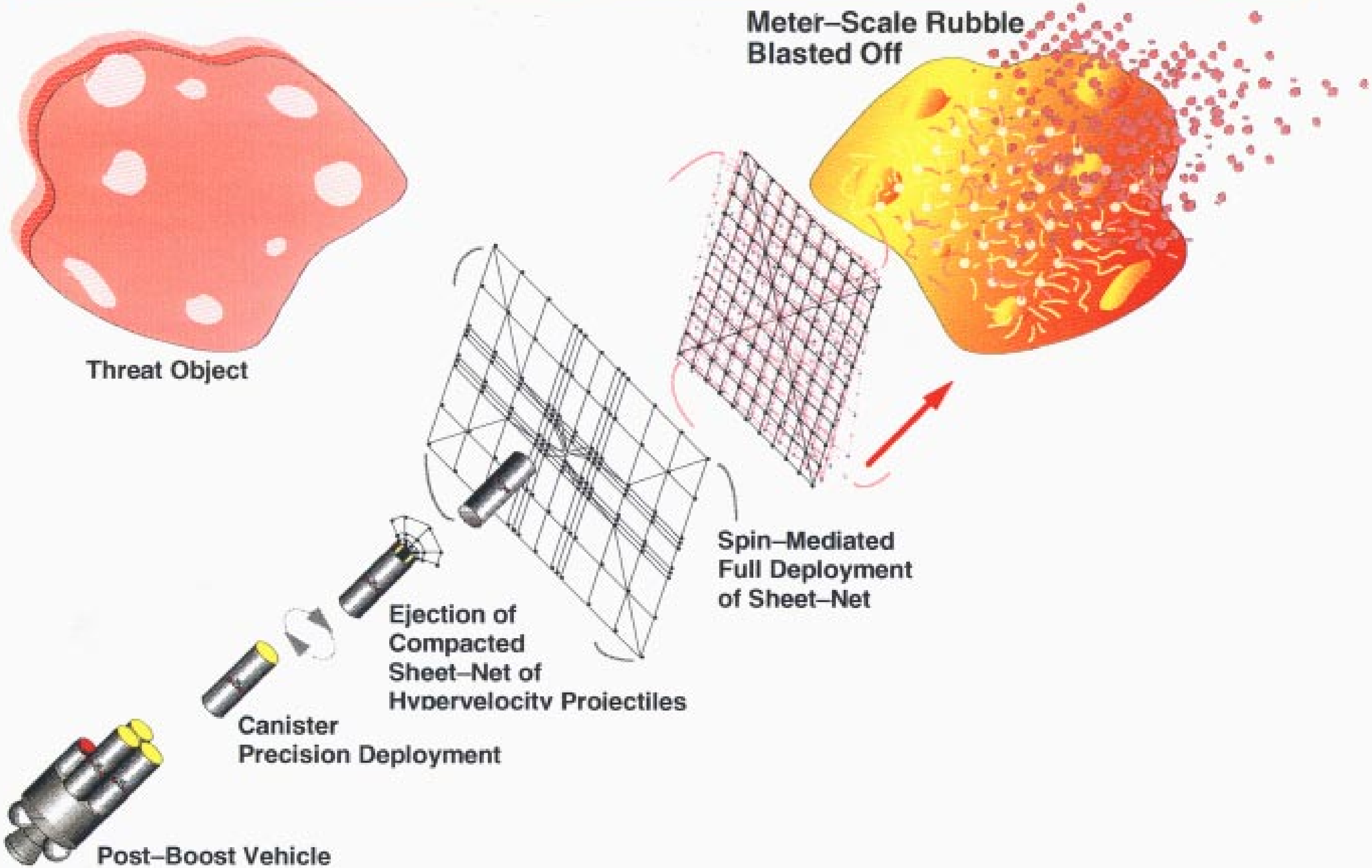


Figure 4

A GENERALLY APPLICABLE APPROACH TO PULVERIZATION



50511-LLW-02

Figure 5

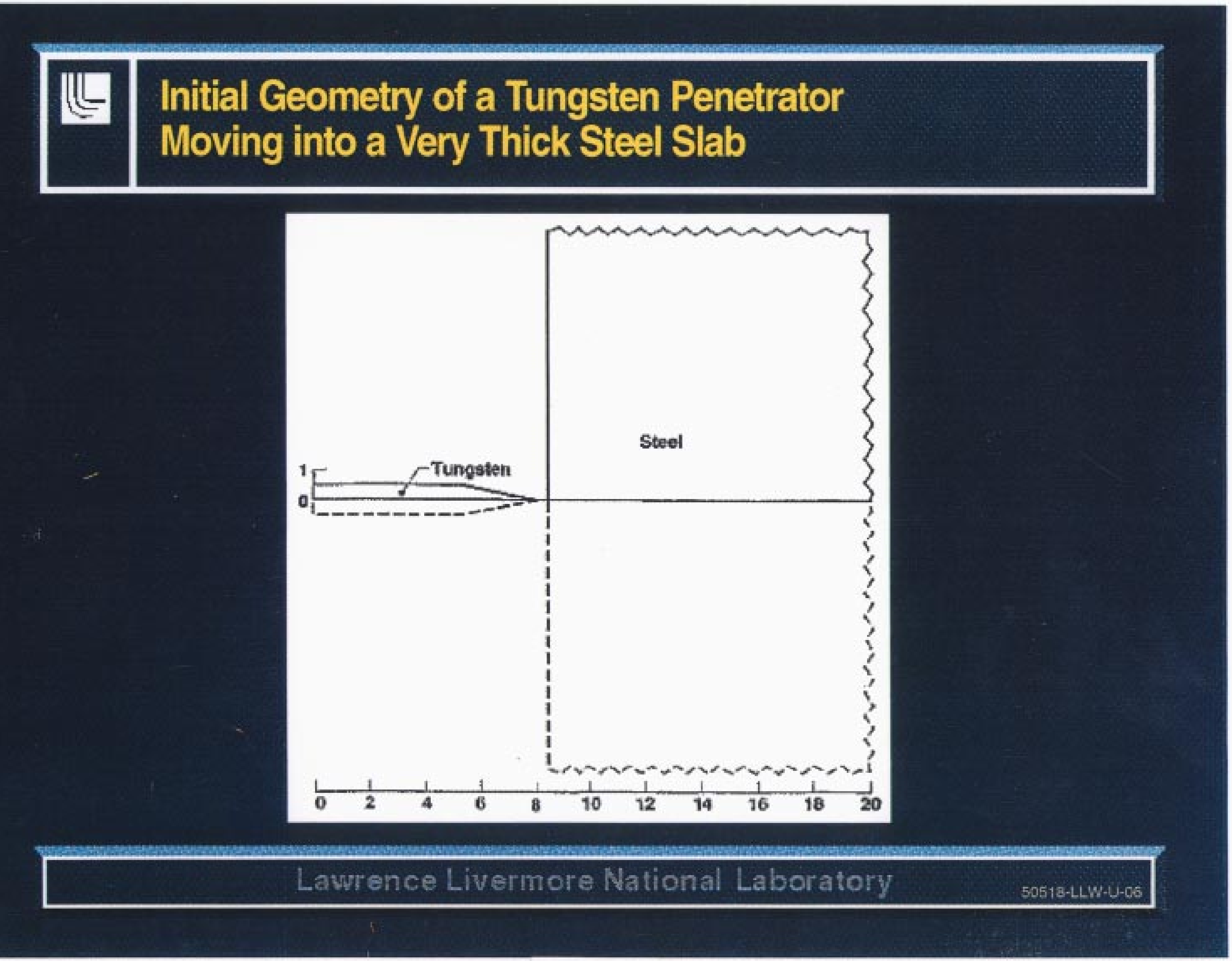

Initial Geometry of a Tungsten Penetrator Moving into a Very Thick Steel Slab
Steel
Tungsten
1
0
0
2
4
6
8
10
12
14
16
18
20
Lawrence Livermore National Laboratory
50518-LLW-U-06

Figure 6A

Evolution of a Cavity

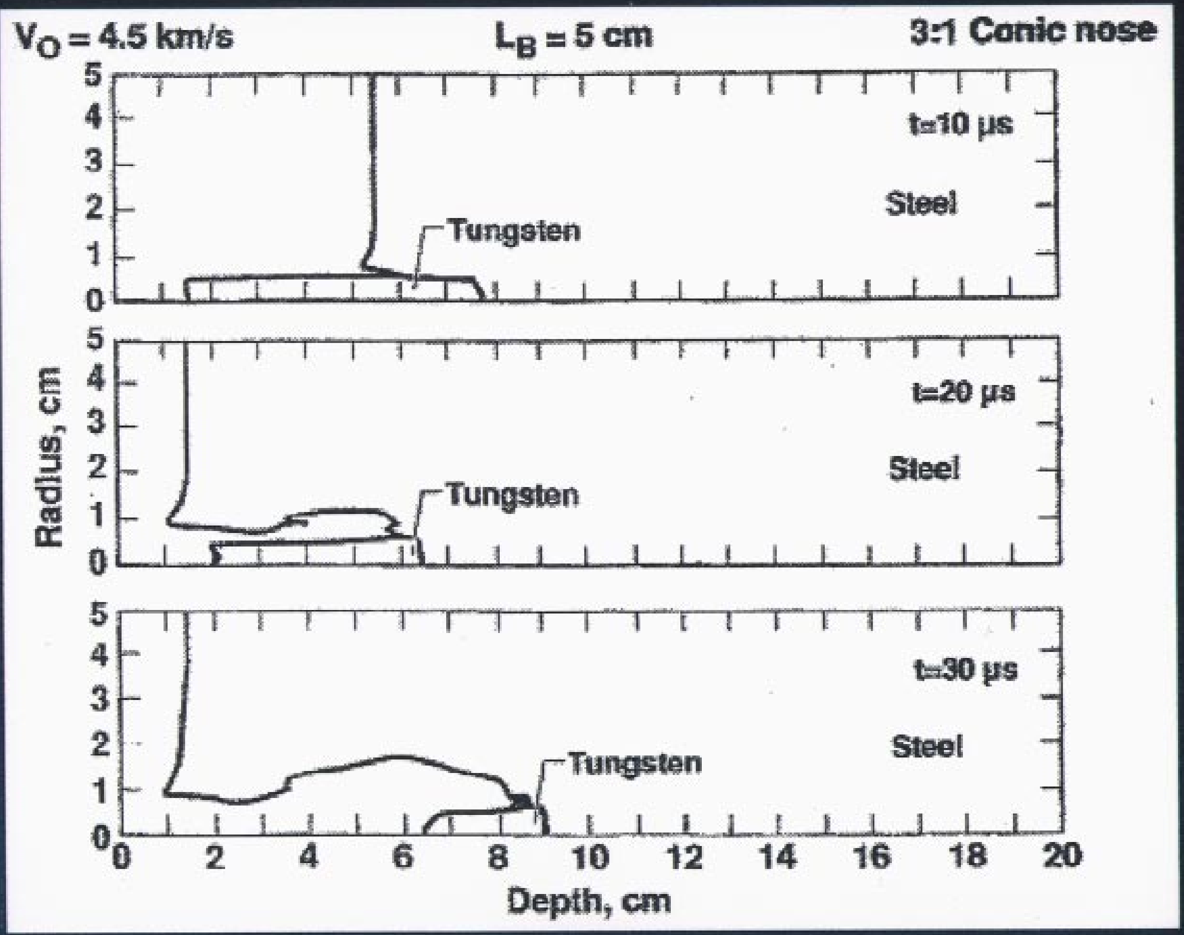
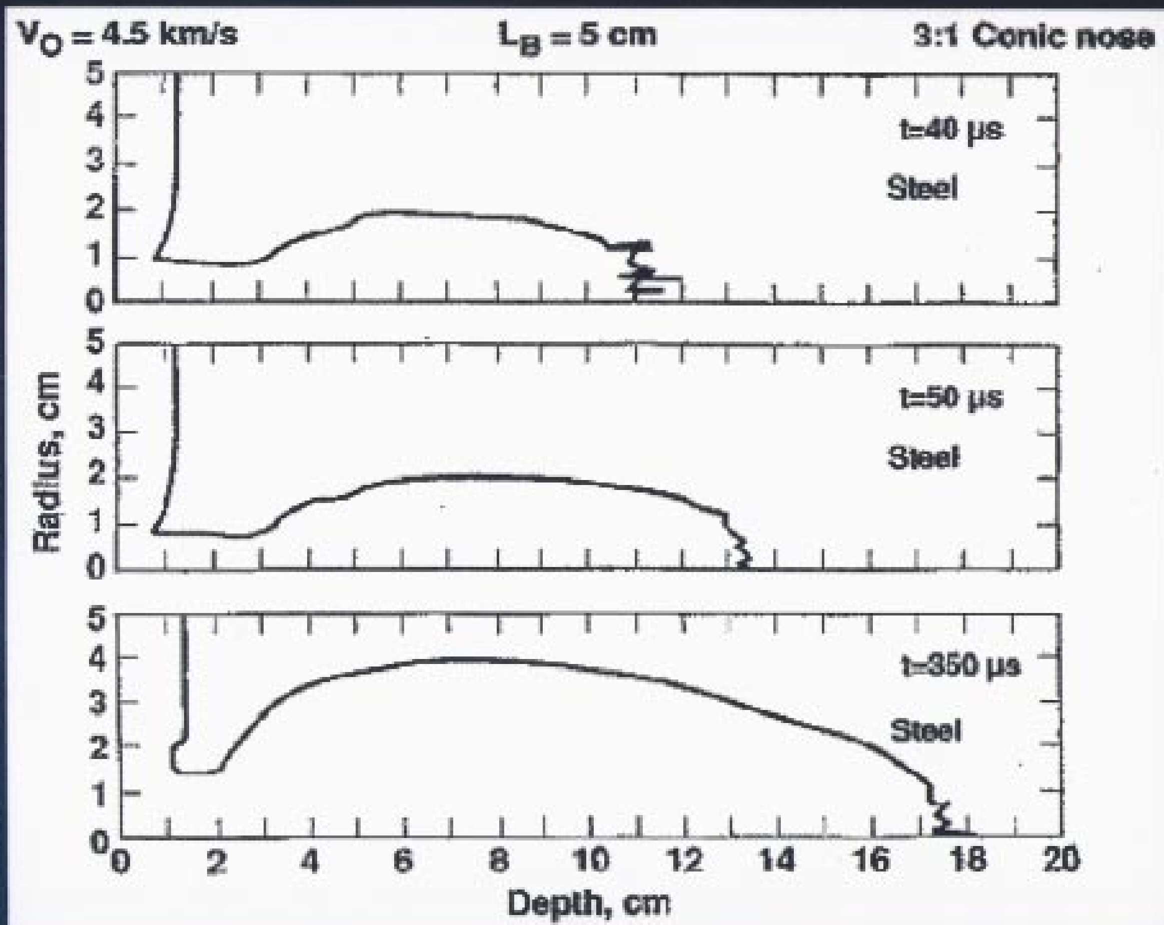


Figure 6B

Evolution of a Cavity (cont.)



The Volume Of The Cavity is Approximately Proportional To The Kinetic Energy Of The Penetrator

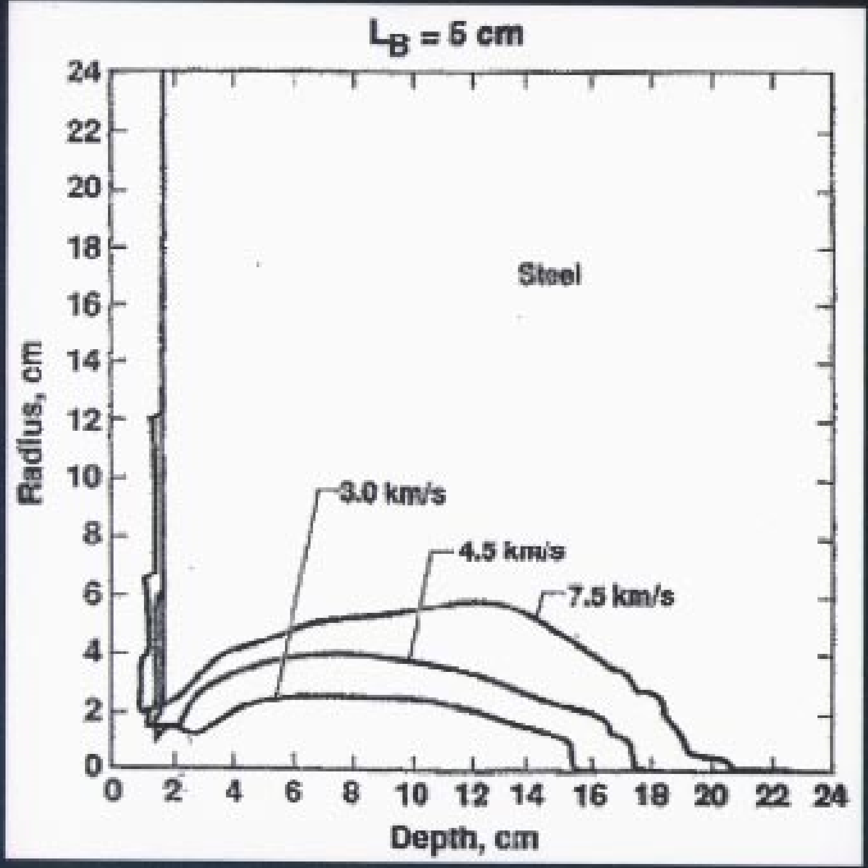


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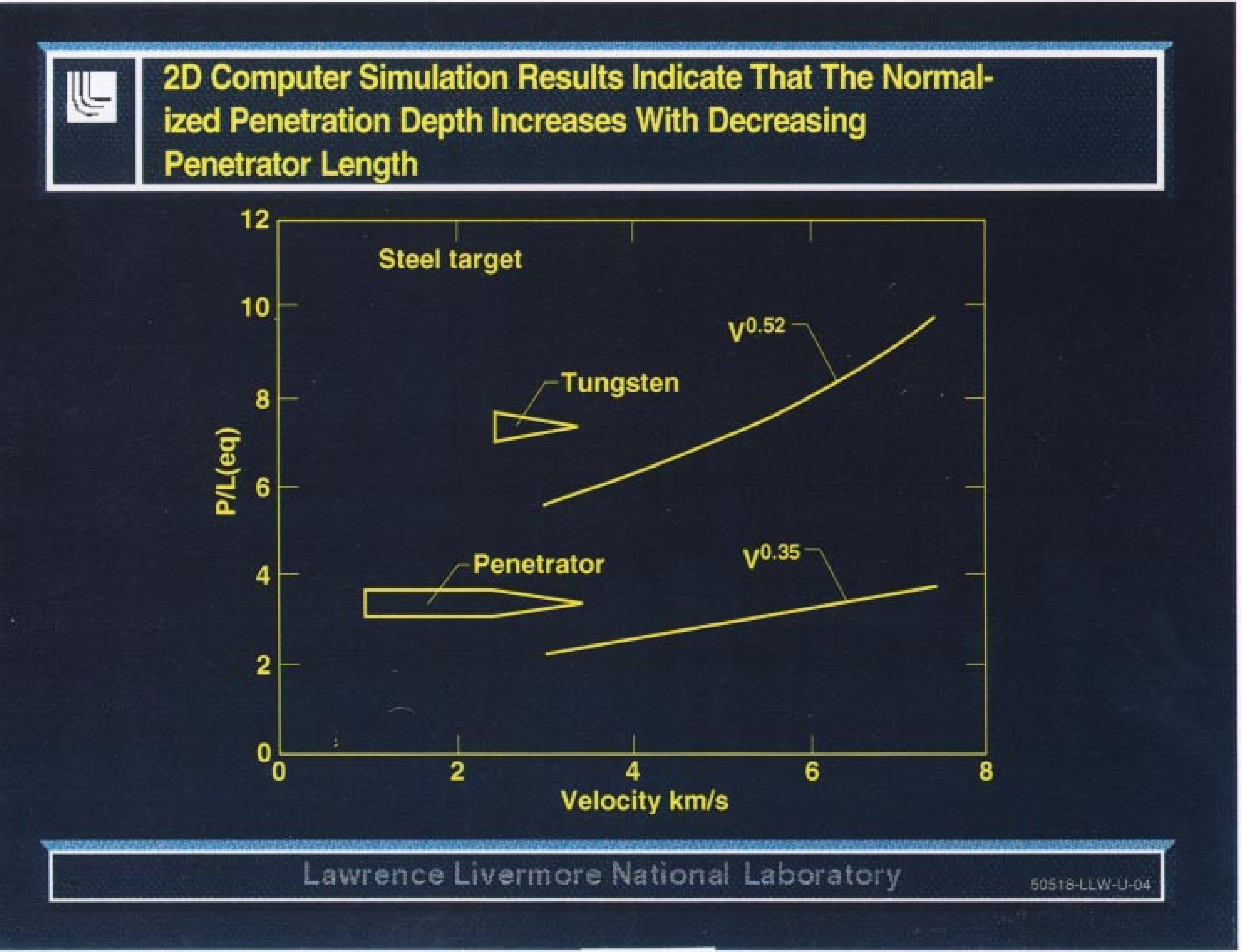
Figure 6D

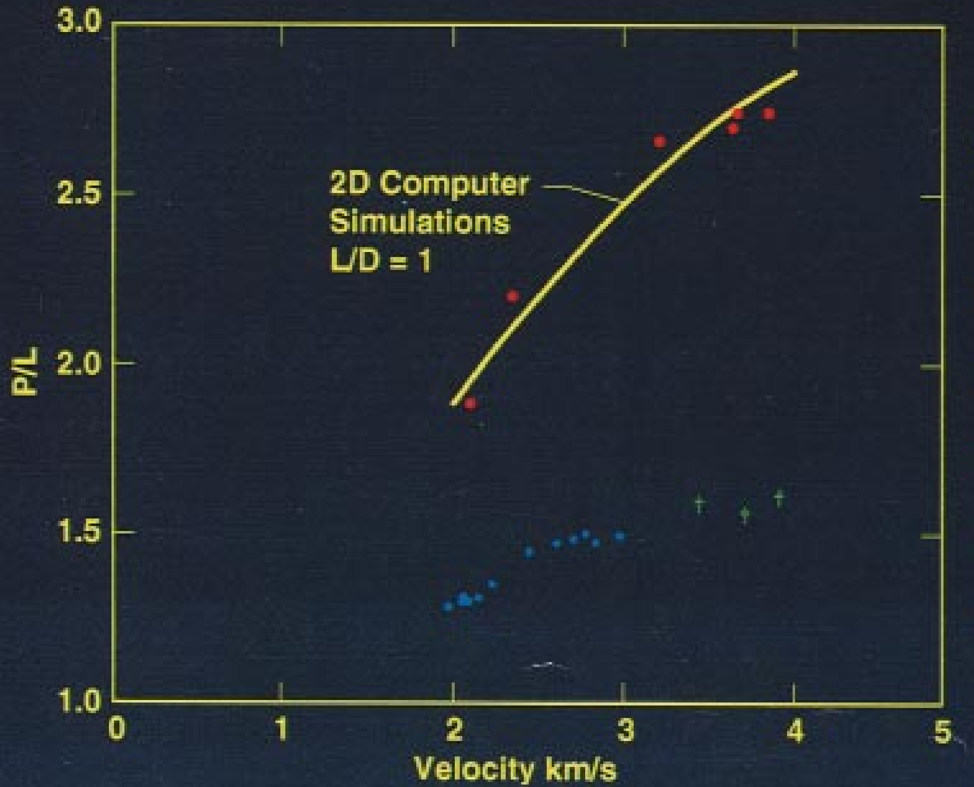


2D Computer Simulation Results Indicate That The Normalized Penetration Depth Increases With Decreasing Penetrator Length
Steel target
Tungsten
Penetrator
V0.52
V0.35
P/L(eq)
Velocity km/s
0
2
4
6
8
10
12
Lawrence Livermore National Laboratory
50518-LLW-U-04

Figure 6E

Calculated Penetration Depths Are In Good Agreement With Experimental Data.

A Segmented String Of Short Penetrators Should Be used To Obtain The Maximum Penetration With The Minimum Mass



Data From:
V. Hohler and A.J. Stilp, Int.J. Impact Eng. 5 323 (1987)

Penetrator: Tungsten sinter-alloy, 17.6 g/cm^3

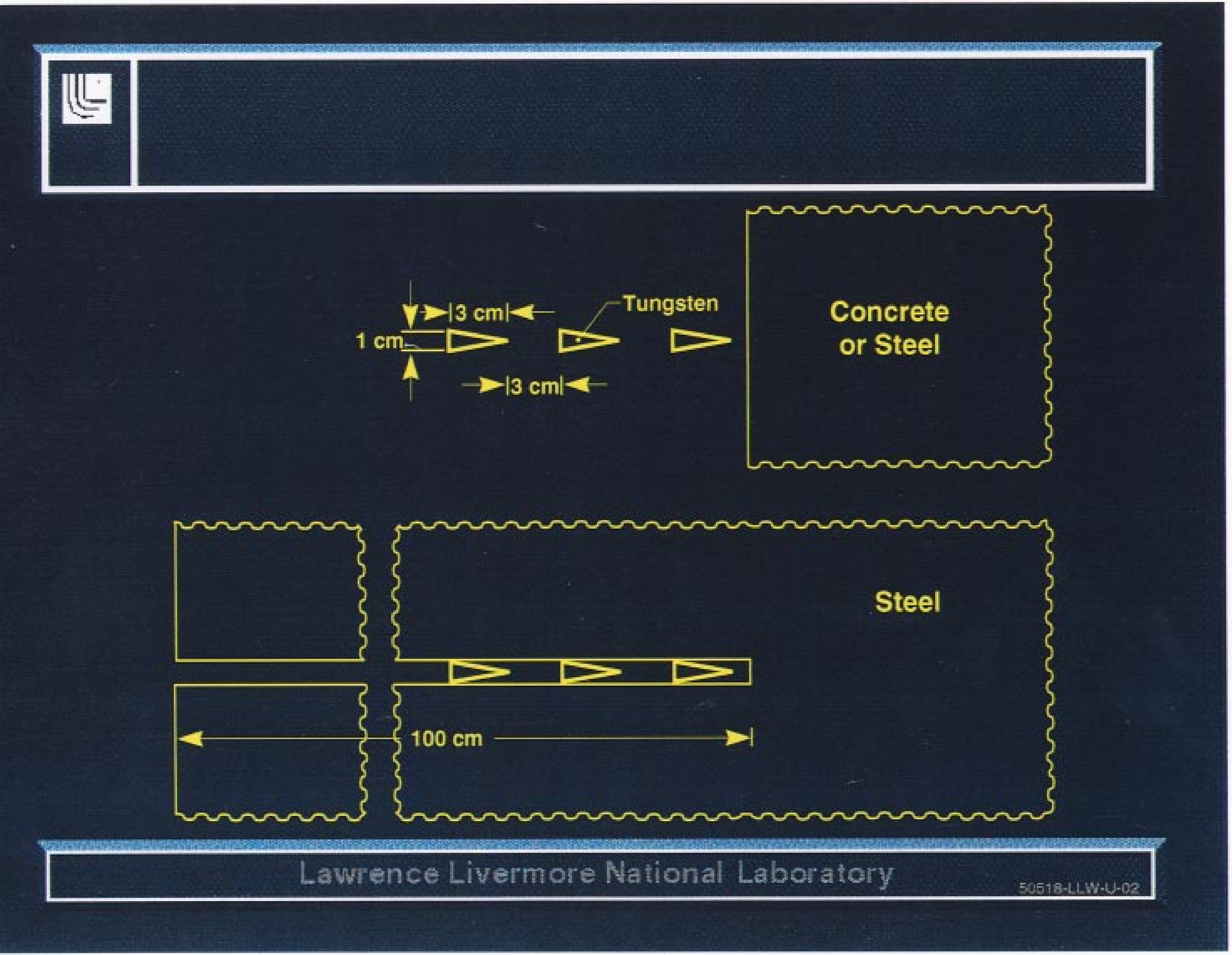
Target: High strength steel

• L/D = 1

† L/D = 9

• L/D = 10

Figure 6F



3 cm
1 cm
3 cm
Tungsten
Concrete or Steel
Steel
100 cm
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50518-LLW-U-02

Figure 6G

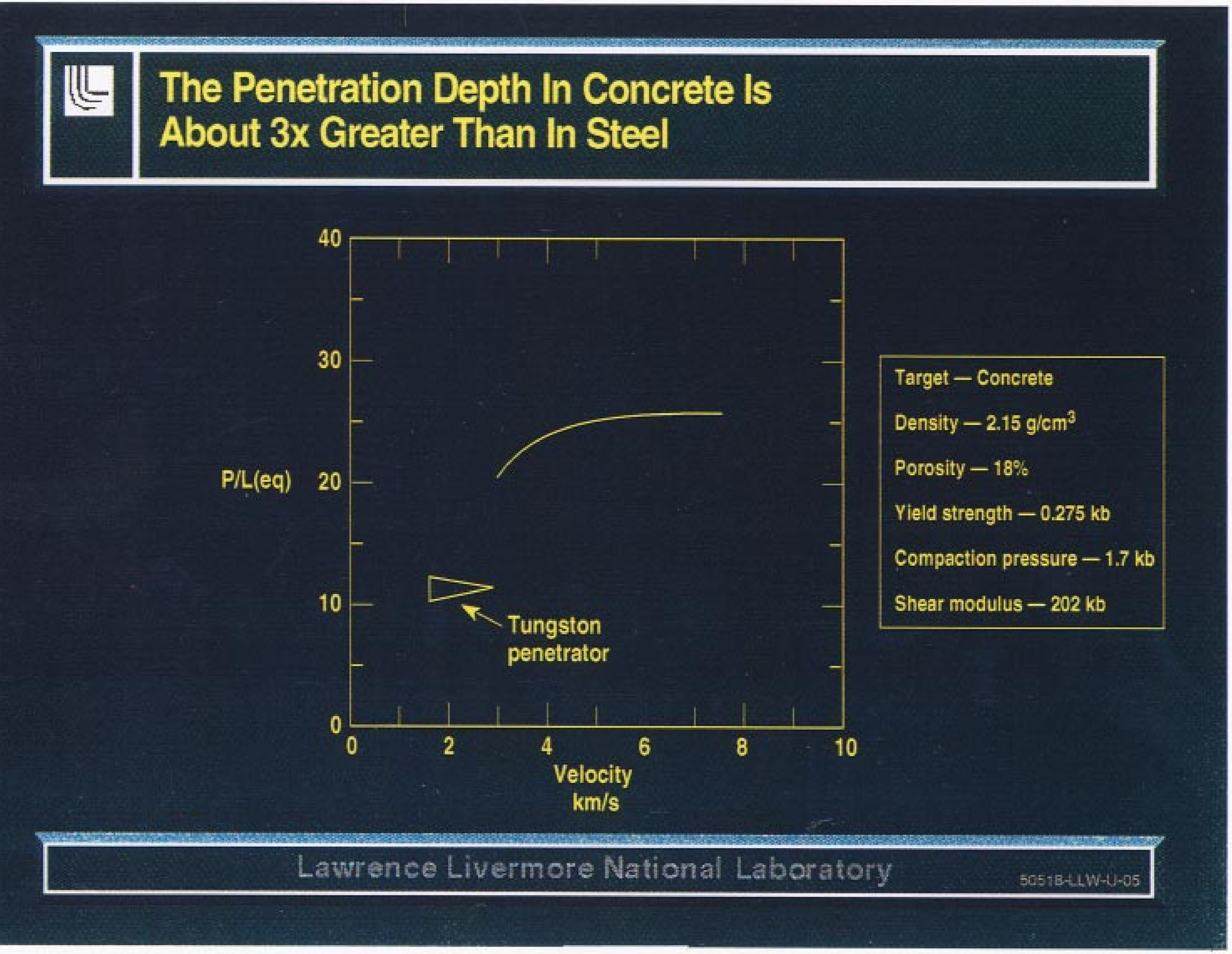

The Penetration Depth In Concrete Is About 3x Greater Than In Steel
P/L(eq)
40
30
20
10
0
0
2
4
6
8
10
Velocity
km/s
Tungston penetrator
Target — Concrete
Density — 2.15 g/cm3
Porosity — 18%
Yield strength — 0.275 kb
Compaction pressure — 1.7 kb
Shear modulus — 202 kb
Lawrence Livermore National Laboratory
50518-LLW-U-05

Figure 6H

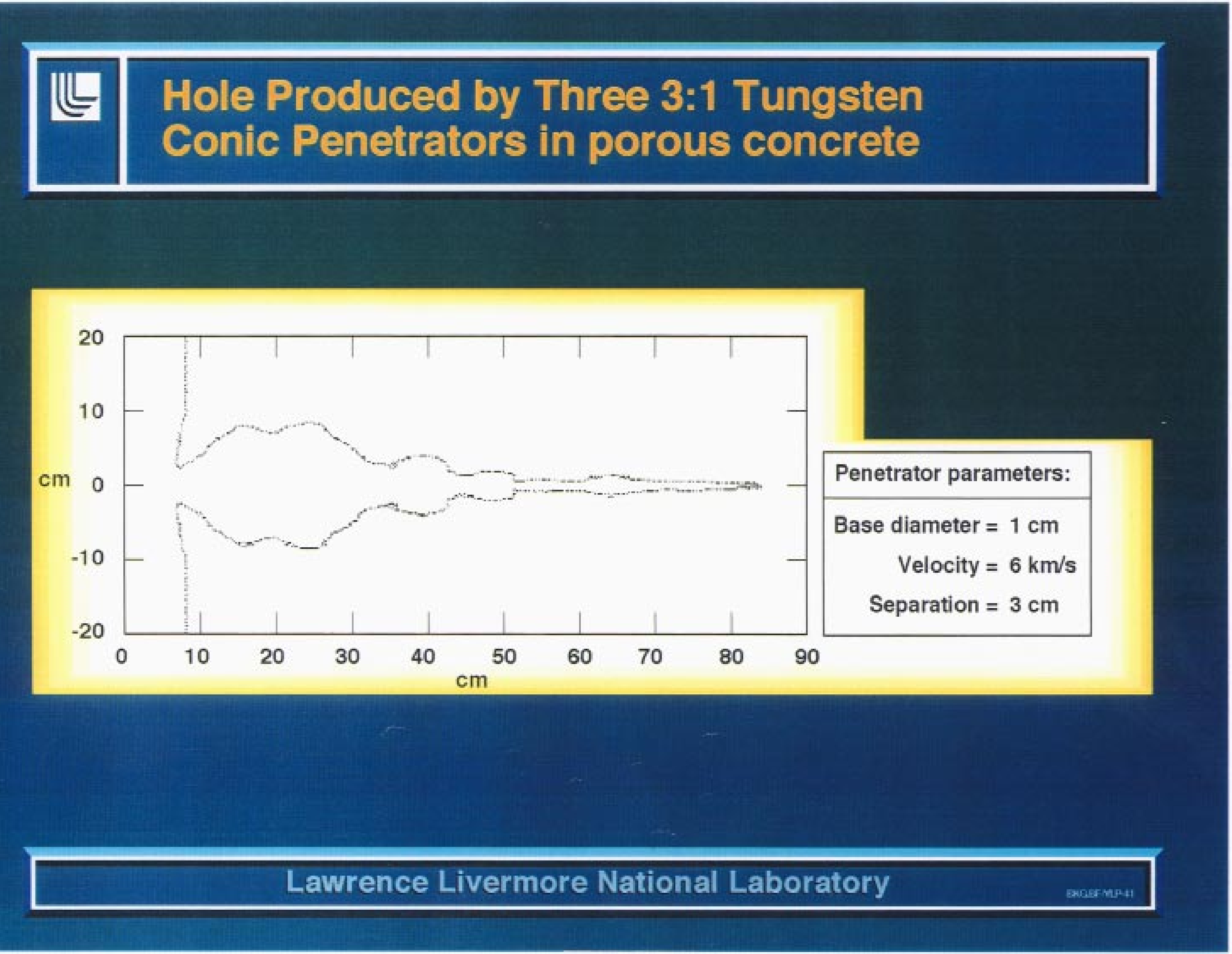

Hole Produced by Three 3:1 Tungsten Conic Penetrators in porous concrete
20
10
cm 0
-10
-20
0
10
20
30
40
50
60
70
80
90
cm
Penetrator parameters:
Base diameter = 1 cm
Velocity = 6 km/s
Separation = 3 cm
Lawrence Livermore National Laboratory

Figure 6I

Figure 6J

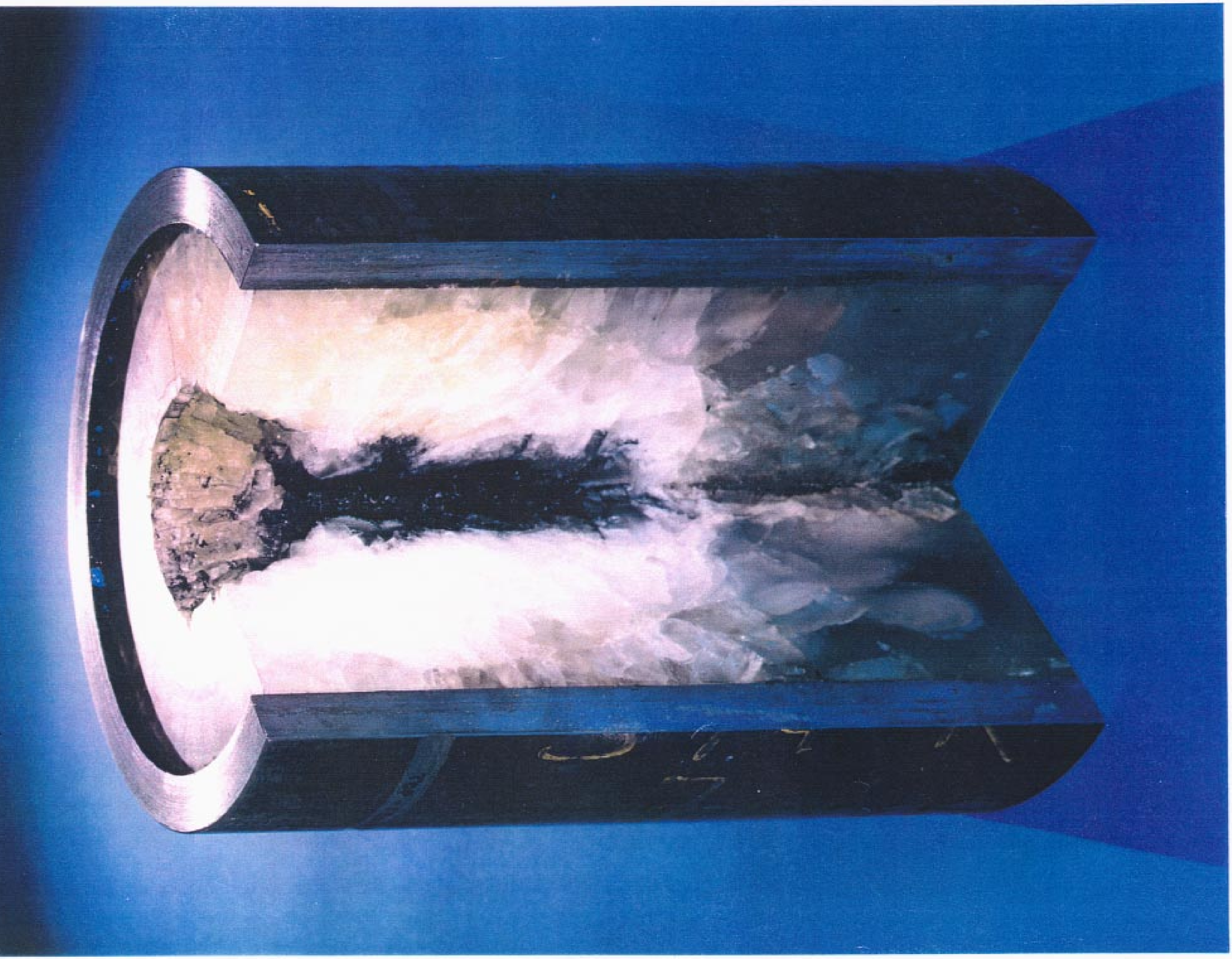


Figure 6K

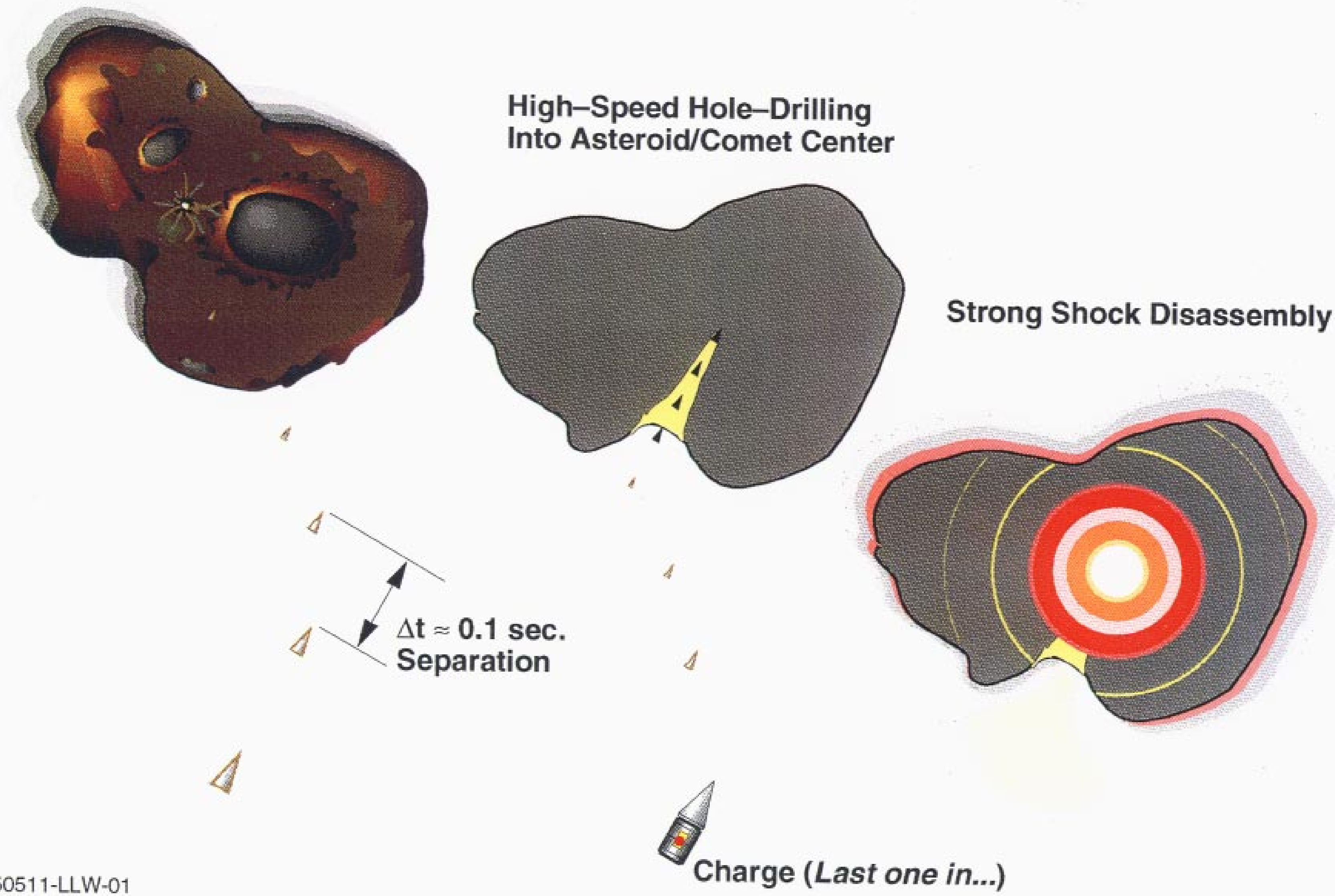
HL.302-08/YLP

Figure 6L

HL.302-01/YLP

Figure 6M

THREAT OBJECT VAPORIZATION

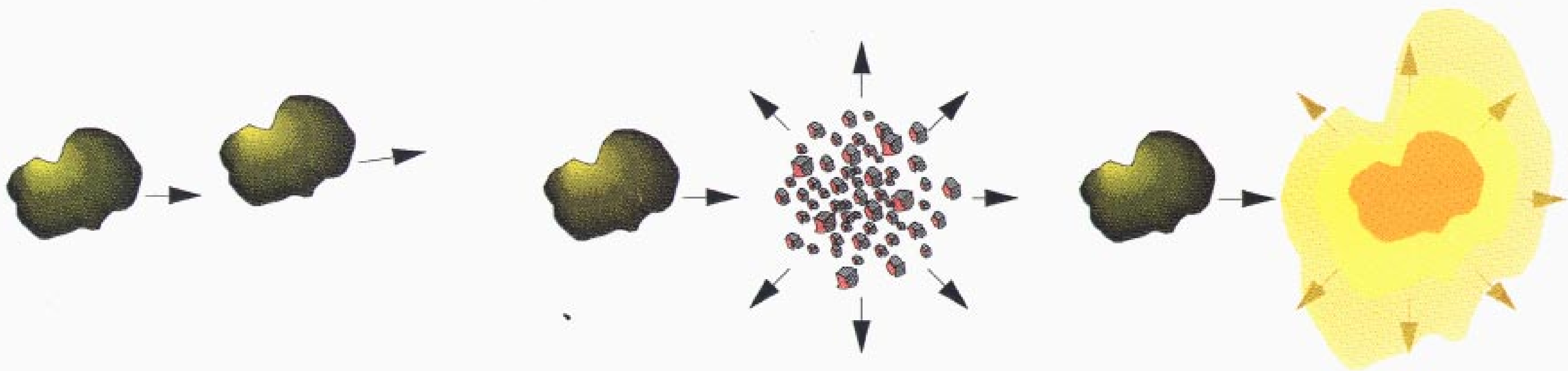


50511-LLW-01

Figure 7

THREAT NEGATION

Deflection | **Pulverization** | **Vaporization**



Required Energies

.01 — .10 J/gm | 10 — 100 J/gm | 1000 J/gm

- **Kinetic Energy:** 10^5 — 10^6 J/gm
- **Nuclear Explosives:** 10^{11} J/gm

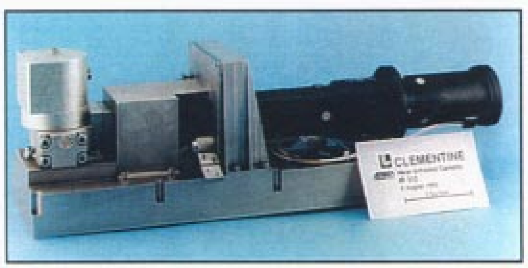
50517-RAH-01

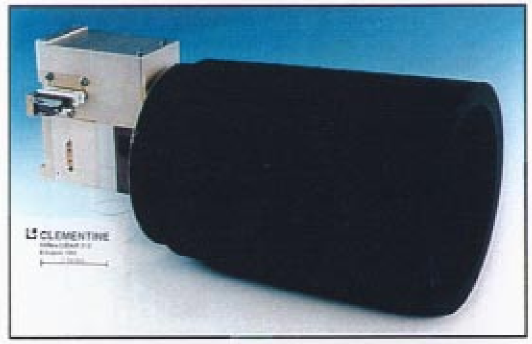
Figure 8

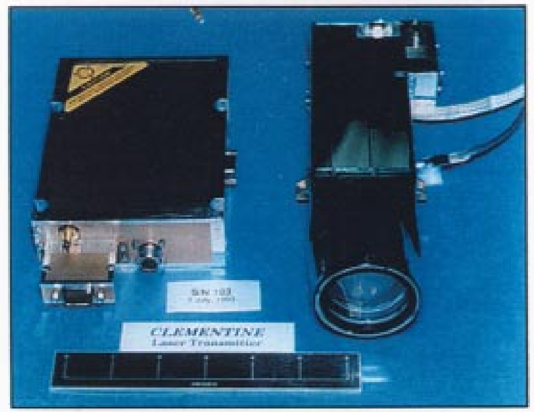
CLEMENTINE
DoD - NASA
Clementine Demonstrates Advanced Technologies Developed By Many Sponsors
DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA
GaAs/Ge Solar Cell Arrays
Variable Conductance Heat Pipes
1750A VHSIC Chip Set
SEPARATION PLANE
SMA ACTUATOR
NOTCH PROVIDES CONTROLLED SEPARATION
INTEGRAL ELECTRONIC HEATER/INSULATION
HIGH STRENGTH ALLOY NUTS, BOLT & WASHERS
Advanced Release Mechanism
Common Pressure Vessel NiH_2 Battery
National / 6.1 / 6.2
1.9 Gb Solid State Data Recorder
Spacecraft Controller (18 MIPS)
NRL
Inertial Measurement Units
REACTION WHEEL
Reaction Wheel
Mission Cameras
Composite Interstage Adapter
BMDO

Figure 9A

Clementine Sensor Suite







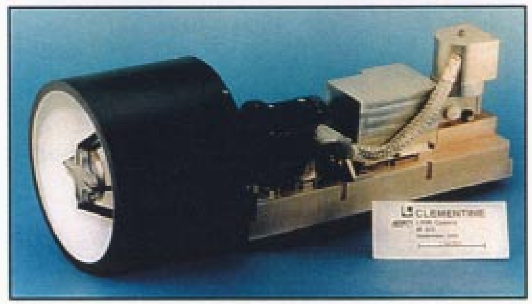


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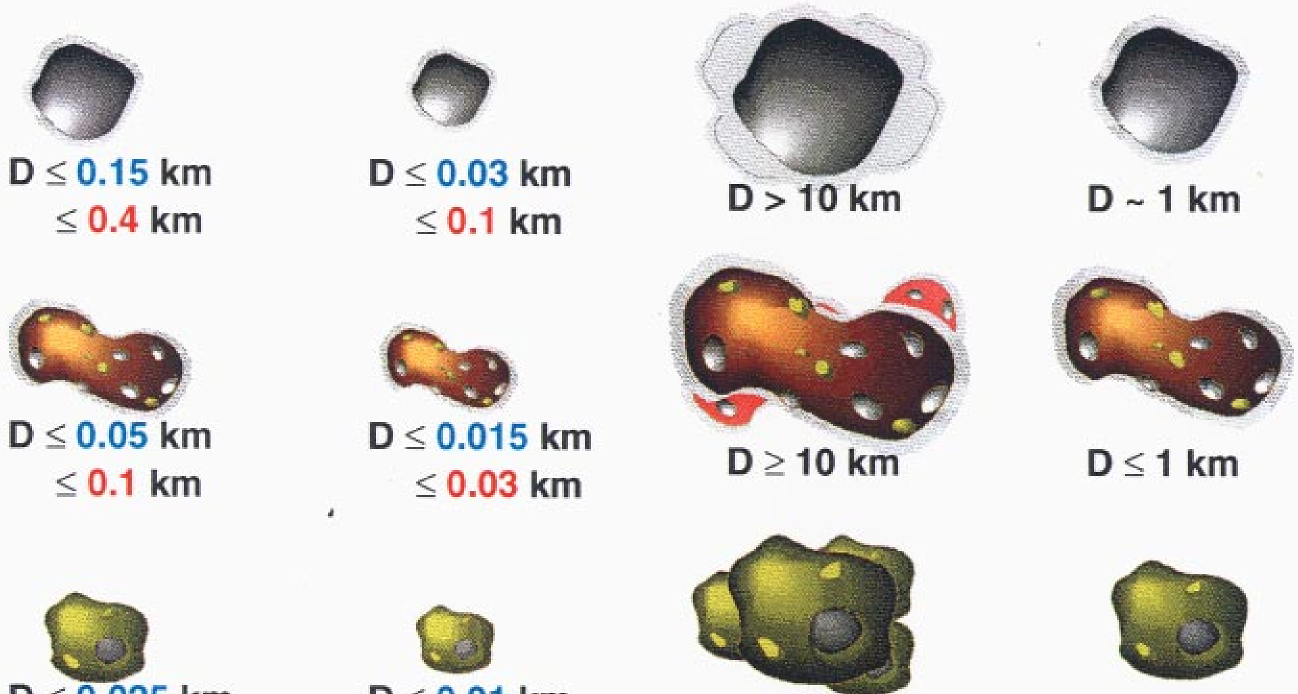
Figure 9B

NEAR–TERM THREAT NEGATION CAPABILITIES

- Contemporary Technology
- Single Heavy–Lift Launch (e.g., ENERGIA or Fleet–of–100 SS–18s)



	Non–Nuclear Pulverization	Non–Nuclear Vaporization	Nuclear Pulverization	Nuclear Vaporization
COMET	D ≤ 0.15 km ≤ 0.4 km	D ≤ 0.03 km ≤ 0.1 km	D > 10 km	D ~ 1 km
STONY ASTEROID	D ≤ 0.05 km ≤ 0.1 km	D ≤ 0.015 km ≤ 0.03 km	D ≥ 10 km	D ≤ 1 km
NICKEL–IRON ASTEROID	D ≤ 0.025 km ≤ 0.05 km	D ≤ 0.01 km ≤ 0.025 km	D ~ 10 km	D ~ 0.5 km
	$E_{mass} \sim 10^4–10^6$	$E_{mass} \sim 10^2–10^3$	$E_{mass} \sim 10^9–10^{10}$	$E_{mass} \sim 10^7–10^8$

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Figure 10

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