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# The Effects of Nuclear Test-ban Regimes on Third-generation–weapon Innovation

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> *The primary reason that we are pursuing nuclear directed energy weapons is to understand the Soviets' capability to design and deploy similar weapons, which would put the US strategic deterrent force or a future defensive system at risk.*
>
> Former US Energy Secretary John S. Herrington*

> *It is by no means certain that a Comprehensive Test Ban would prevent the Soviets from developing a new generation of nuclear weapons, although that would assuredly be the effect of a total testing ban on the US.*
>
> Former Director of Los Alamos National Laboratory, Donald Kerr†

Under the rationale of assessing potential Soviet threats, several third-generation–weapon concepts are being actively studied in the US. This paper presents a technical analysis of the physical principles and likely capabilities of three nuclear directed-energy concepts (x-ray lasers, nuclear kinetic-energy weapons, and microwave devices) and describes the implications for their development of threshold test bans at thresholds above and below 1 kiloton. Inertial Confinement Fusion, specialized non-nuclear weapon effects simulation, and seismically quiet containment

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* Response to questions by Senator Mark Hatfield, in "Hearings on Energy and Water Development Appropriations for FY 1987," part II, before a subcommittee of the Senate Committee on Appropriations, 99th Congress, 2nd Session, p.642 (1986).

† Prepared statement, submitted to the hearings of the House Foreign Affairs Committee, subcommittee on Arms Control, International Security, and Science, "Proposals to Ban Nuclear Testing," 18 May 1985, p.93.

vessels for low-yield tests may complicate arguments about the verifiability and long-term effectiveness of a test ban.

## INTRODUCTION

Although a comprehensive test ban (CTB) has been proclaimed to be a goal of the US ever since the Kennedy Administration signed the Limited Test Ban Treaty (LTBT) in 1963, it has remained elusive. The test-ban debate has had a tortuous history, repeatedly encumbered by arguments about verifiability; implications for reliability of the stockpile, warhead safety and security, and vulnerability of weapons in nuclear environments; and the need for force modernization.[*]

The verifiability of test-ban regimes—and the significance of cheating—have always been contentious issues. Recently, however, both technical and political factors have helped support attempts to further restrict the yields of underground tests, which are currently permitted only up to yields of 150 kilotons by the 1974 Threshold Test Ban Treaty. Numerous experts have advocated a low-yield test-ban as a first step toward a comprehensive ban,[†] and the House defense-budget resolutions in 1986 and 1987, if they had been supported by the Senate, would have withheld funds for any US nuclear tests above 1 kiloton. Recent studies of seismic capabilities using networks of in-country seismometers have also argued for detection at thresholds of about 1 kiloton.[‡] A higher threshold could be made more

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* For an excellent discussion of these issues, see, for example, Steve Fetter, "Stockpile Confidence Under a Nuclear Test Ban," *International Security*, 12, 3 (Winter 1987–1988), pp.132–167; John D. Immele, Paul S. Brown, and Steve Fetter, "An Exchange on Stockpile Confidence," *International Security*, 13, 1 (Summer 1988), pp.196–215; and Steve Fetter, *Toward a Comprehensive Test Ban* (Cambridge, Massachusetts: Ballinger, 1988).

† This was the consensus of the overwhelming majority of technical and policy experts at the Belmont Conference, held 29 September–1 October 1988 outside Washington DC, whose participants included Richard Garwin, Ray Kidder, Christopher Paine, Lynn Sykes, the current author, and more than 20 others. See Belmont Conference on Nuclear Test Ban Policy, "Phasing Out Nuclear Weapons Tests; A Report to the President and Congress," (Washington DC: Natural Resources Defense Council, 1989).

‡ US Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties*, OTA-ISC-361 (Washington DC: US Government Printing Office, May 1988). See also, Jack R. Evernden, C.B. Archambeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic

restrictive by combining it with a quota system to limit the *number* of tests at given yields.

Some have argued, however, that the development of third-generation weapons—devices powered by nuclear explosions that either *transform, select,* or *direct* their energy in a unique way—might take place even with a threshold of 1 kiloton in force.* If this is true, and if these weapons are believed to be a serious threat by either superpower, then a 1-kiloton threshold might do no more than lull many in the arms-control community into quiescence while legitimizing the development of a dangerous new arms race. The only alternative would appear to be a comprehensive test ban.†

To complicate matters further, the official rationale for third-generation research in the US is to assess the threat that *Soviet* innovations might pose to US nuclear forces and military systems.‡

The following analysis, based on unclassified sources, will address the physics and capabilities of certain third-generation weapons, and the ways in which a low-yield test ban would affect their development. Three specific concepts will be discussed: x-ray lasers (XRLs), nuclear-powered kinetic-energy weapons (NKEWs), and enhanced microwave devices. Table 1 provides a basic summary of the issues associated with each.

The relevance to the development of these weapons of Inertial Confine-

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Data," *Reviews of Geophysics*, **24**, 2 (May 1986), p.149; and William J. Hannon, "Seismic Verification of a Comprehensive Test Ban," *Science*, **227**, 4684 (18 January 1985), p.251.

* A third-generation weapon is best characterized by the manner in which it delivers energy to a target once it explodes, rather than by its delivery vehicle—the rocket, aircraft, or satellite that carries it. Because of the possibility of enhancing lethality at great distances by directing certain forms of energy into a narrow beam, there has been considerable interest in the potential for low-yield explosions to power these devices. Cf. Theodore B. Taylor, "Nuclear Testing is a Pandora's Box," *FAS Public Interest Report*, **39**, 10 (December 1986), p.9, and "Third Generation Nuclear Weapons," *Scientific American*, **256**, 4 (April 1987), p.30.

† For the purposes of this paper, a "comprehensive" test ban is taken to refer to all nuclear explosions *except* those small enough to be contained in above-ground vessels surrounded by permanently occupied research facilities.

‡ While this rationale attempts to counter allegations that the Strategic Defense Initiative is seeking to develop third-generation weapons for their own sake, it does little to mitigate fears that such pursuits may indeed be the beginning of a new arms race with the USSR. The "exploratory" justification for these programs makes sense only if the research itself proves the concepts to be utterly useless—a conclusion that a finite amount of developmental research can rarely if ever claim with certainty.

ment Fusion (ICF), a High Energy Density Facility (HEDF), and non-nuclear weapon-effects simulation will also be discussed. As will be seen, the significance of these technologies and low-yield testing to third-generation weapon development—while not now posing a serious threat to security—are both likely to increase with time. Any low-threshold or comprehensive test-ban proposal must take this into consideration.

**Table 1:** Comparison of some potential third-generation devices

| | X-ray laser | Nuclear KEW | Microwave device |
|---|---|---|---|
| *Number of tests (through 1987)* | ≈6 | ≥1 | ? |
| *Missions* | ASAT<br>BMD (?)<br>Midcourse discrimination (?) | Midcourse discrimination or kill<br>Defeat salvage fusing<br>ASAT (?)<br>Battlefield (??) | Attacking mobile ICBMs, and $C^3$<br>Air Defense (?)<br>ASAT (?) |
| *Basing* | Space<br>Pop-up | Space<br>Pop-up (?)<br>Theater (??) | Space<br>ICBM (?)<br>Underground (??) |
| *Competitors* | Other DEWs<br>Other KEWs for ASAT and BMD | Neutral particle beam<br>Chemical lasers | Gyrotrons and vircators<br>Explosive flux generators<br>FELs |
| *Countermeasures* | Shielding (?) | Air in path of beam<br>Shielding (?) | Shielding<br>Fiber optics<br>Hardened circuits |
| *Uncertainties* | Physics<br>Pointing | Vaporization of particles<br>Damage to other space-based components | No observable damage<br>Focusing of beam<br>Propagation in air |

This table summarizes the major issues associated with the third-generation concepts discussed in the text. Entries for mission and basing are conjectural, indicating only the range of ideas that may be under consideration

## THE GROWING INTEREST IN THIRD-GENERATION WEAPONS

Five nuclear explosive-powered directed-energy weapons (NDEWs) are being examined by the US Department of Energy (DoE) and the Strategic Defense Initiative Organization (SDIO):* XRLs (code-named Excalibur), NKEWs (code-named Prometheus), microwave weapons, optical-wavelength lasers, and particle beams. Of these, there have been nuclear tests of at least three—XRLs, NKEWs, and one other,† probably a microwave device.

The program in NDEW research, formally begun in 1985, grew to funding levels of $350 million in both fiscal years (FYs) 1987 and 1988. Even though this is but a small fraction of the costs of overall nuclear force modernizations, and Congress subsequently scaled it back to $330 million and $220 million in FYs 1989 and 1990, respectively, the issues raised by third-generation weapons continue to be portentous. An article in *Time* magazine‡ claims "the debate is not over whether these weapons can be developed but whether they should be" and displays artists' conceptions of microwave beams destroying the Pentagon and naval battleships, and an orbiting nuclear cannon destroying re-entry vehicles (RVs) in space. That article implies that the "puny" 40-ton "Hazebrook" explosion, detonated underground on 3 February 1987 in Nevada, might have been a test for just such a NKEW.

The rhetoric of knowledgeable officials attempting to sell the idea of NDEWs is just as excited. The director of DoE's Weapons Research, Development, and Testing Division has said that the Prometheus device, "if feasible, would make an incredible weapon...," and that nuclear-pumped optical lasers "show great theoretical potential for disabling offensive *and*

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* "Energy and Water Development Appropriations for 1987," part 6, Committee on Appropriations, US House of Representatives, p.1394. See also Steven Aftergood, "Nuclear Aspects of the Strategic Defense Initiative," paper presented at the American Physical Society Symposium of the Forum on Physics and Society, Arlington, Virginia, 21 April 1987, p.3.

† "Department of Defense Appropriations for 1987", Part 5, Committee on Appropriations, US House of Representatives, p.614. The one known NKEW test (having yield under 20 kilotons) occurred on 17 August 1985 and was named "Chamita."

‡ Michael D. Lemonick, "A Third Generation of Nukes," *Time*, 25 May 1987, p.36. See also, "SDI's 'Nuclear Shotgun' on Pentagon Fast Track," *Washington Times*, 22 April 1987, p.1A; and Taylor, "Third Generation Nuclear Weapons," pp.30–39.

defensive weapons, even through the atmosphere."* Another report, published in 1980, implied the existence of a nuclear-pumped rare-gas halide (eximer) laser system. An unnamed "expert" from Livermore Lab was reported to have said that the weapon employed 50 pulsed lasers in a ring around and directly pumped by the detonation of a small nuclear device, that it would be able to engage targets for ballistic-missile defense at a range of 7,500 kilometers, and that it could be placed in orbit "within 2 or 3 years of approval."†

This publicity occurs despite a lack of analysis in the unclassified literature about the technical feasibility or military significance of the concepts.

However, third-generation breakthroughs have not yet undermined the potential for a low-yield or comprehensive test-ban to prevent a third-generation arms race. Until complex third-generation principles are understood and made to work efficiently, the development of weapons such as the x-ray laser would be greatly inhibited in the absence of testing at higher yields. Second, quick breakthroughs in development of exotic weapons at *any* yield are highly unlikely even under a 1-kiloton threshold ban because of the likely undermining of the broad technical, political, and financial support needed for nuclear-weapon development. However, once the details of actual third-generation designs are understood, and the mechanisms made more efficient through continued testing and experimentation, low-yield tests may become more relevant, and fears of militarily significant cheating on a low-yield test ban could well become more serious.

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* Richard D. Hahn, quoted in "Strategic Connections in Space," *Air Force Magazine*, August 1987, pp.78–84.

† "Particle Beams and Laser Weapons, Part I," *Aviation Week and Space Technology* ,28 July 1980, p.34. There is little doubt that nuclear pumping of eximer lasers has been considered, but the details are classified. A nuclear detonation would probably not be very useful for pumping eximer lasers because of its extremely fast release of energy, tending to over-pump the lasant gas much faster than the eximer's optimal 0.5–1-microsecond time-scales. Cf. "Report to the APS of the Study Group on Science and Technology of Directed Energy Weapons," *Reviews of Modern Physics*, 59, 3, part II (July 1987), pp.S47–S54.

**Table 2:** Nuclear testing thresholds and their significance

The regimes of nuclear testing, ordered by yield. For each threshold, the possible activities are listed according to their relevance to first- and second-generation weapons or third-generation development. The uncertainties associated with devices listed above and below 1 kiloton are discussed in the text

| **Threshold*** | **Regime** | **First and second generation** | **Third generation** |
|---|---|---|---|
| 0.0 | Non-nuclear | PALs†<br>Warhead inspection and remanufacture | Effects-simulations, for "threat assessment" |
| 0.2 kilograms‡ | Hydronuclear | One-point safety tests<br>Design of basic fission bomb | — |
| 100 kilograms | *Carter Administration threshold used to define "comprehensive"* | | |
| 300 kilograms | ICF | Materials effects studies<br>Maintain fusion expertise | Some third-generation physics |
| 10 tons | Tactical | *example:* US W54 atomic demolition munition | *NKEWs ?*<br>*Microwave devices ?* |
| 300 tons | HEDF; "Quiet" | Maintain weapon expertise | *Other third-generation ?* |
| 1 kiloton | Seismic detection<br>*High confidence* | Neutron warheads | Thermonuclear shaped charges |
| 10 kilotons | Boosting | New primaries<br>Reliability testing | Compact sources for third generation (?) |
| 150 kilotons | TTBT *since 1974* | New designs up to 1 megaton | XRL (?) |
| Above-ground testing<br>*Banned by LTBT since 1963* | | Full effects testing (EMP, cratering, fallout, etc.) | NDEW propagation<br>Detailed threat assessment |

* The "threshold" yield estimates the smallest testing limit that still allows listed activities to be accomplished. (Activities listed at *higher* yields are extremely difficult or impossible at lower thresholds.)

† Permissive Action Links (PALs) are electromechanical devices incorporated into most warhead designs to prevent accidental or unauthorized arming and fusing.

‡ Threshold yields are expressed in the usual way as *equivalent* weights of high explosive—that which would release the same amount of energy as the (nuclear portion) of the detonation. Thus "hydronuclear" detonations release an amount of *nuclear* energy equivalent to only a fraction of a kilogram of TNT, even though those tests might use a much greater quantity of high explosive itself.

## LOW-YIELD TESTING REGIMES AND THIRD-GENERATION WEAPONS

It has recently been learned that, in addition to the 5 percent of reported US tests whose yields were under 1 kiloton, 20 percent of all US tests during the last 25 years have *not* been publicly reported, and most of those have also had yields under 1 kiloton.* There are therefore several distinguishable yield-regimes above *and below* 1 kiloton. The significance of these thresholds for first-, second-, and third-generation weapons is outlined in table 2.

The lowest yield-regime, bounded by the definition of "comprehensive" test ban agreed to during the test-ban negotiations of the Carter Administration, includes nuclear yields up to 100 kilograms equivalent of high-explosives.† For third-generation design, effects-simulation is probably the most significant activity in this category. One facility for this purpose, called the Simulation Test Laboratory (STL) at Sandia National Laboratory, was completed in late 1987 at a cost of over $40 million after four years of development. It includes nuclear reactors run in neutron-burst mode, x-ray and gamma-ray sources produced by high-energy electron beam accelerators, electromagnetic-pulse (EMP) simulators, and continuous radiation sources that utilize vast reservoirs of highly radioactive isotopes. The STL has the capability to permit "more cost-effective weapon development than if only underground nuclear weapon testing in Nevada were used."‡

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* See, for example, Ray E. Kidder, "Militarily Significant Nuclear Explosive Yields," *FAS Public Interest Report*, 38, 7 (September 1985), p.2; and William J. Broad, "Seismic Data Show 117 Secret U.S. Atom Tests," *New York Times*, 17 January 1988, p.1.

† First- and second-generation weapon testing within this yield range include the design of most types of permissive action links (PALs) and the periodic disassembly, inspection, and remanufacture of deteriorating warheads. Basic gun-barrel fission bombs can be designed reliably without nuclear tests, as was the case with the bomb dropped over Hiroshima. In addition, a procedure called hydronuclear testing can be employed to test warheads for "one point safety." With this method, a series of detonations is performed, each with a bit more nuclear material than the last, until a small nuclear yield is obtained. Over 35 hydronuclear tests were performed during the testing moratorium of 1958–1961, each with a nuclear yield equivalent to much less than 1 kilogram of dynamite. Robert N. Thorn and Donald R. Westerveldt, "Hydronuclear Experiments," Los Alamos Report LA-10902-MS, February 1987, p.6.

‡ Sandia National Laboratory News Release, 21 April 1983; and "Sandia National Laboratory Radiation Facilities," third edition, SAND83-0598, December 1985. At the STL, the Hermes III electron accelerator and the Saturn accelerator (which is a direct

The next regime, containing the four orders of magnitude between 100 kilograms and 1 kiloton, could be described as potentially militarily significant, but also potentially "quiet." One activity within this range is Inertial Confinement Fusion (ICF), whose *microexplosion* yields up to about 300 kilograms high-explosive equivalent could be contained in above-ground reactor vessels. In the event of a test ban, ICF would provide an experimental base for extensive studies of materials effects and would be a key factor in maintaining a cadre of experts in fusion physics and diagnostics—the basis for weapon design and certification. But ICF microexplosions might also act as a useful research tool in the study of XRL physics, microwave generation, and other exotic weapon phenomena.

At higher yields, testing becomes progressively more significant in a military sense. Tactical nuclear weapons, such as the W54 Special Atomic Demolition Munitions, have already been designed, tested, and deployed with yields as low as 10 tons.

The practical cutoff for explosions that can be contained in seismically quiet vessels is around 300 tons, and indeed, a design for a so-called High Energy Density Facility (HEDF), has been under study since 1981 by scientists at Livermore. This facility would be located at the Nevada Test Site and would consist of a seismically quiet underground chamber able to contain nuclear detonations up to 0.3 kilotons. It would be reusable, operating with about one test per week.* The cost to build such a facility has been estimated at several hundred million dollars, which does not seem prohibitive if compared to the current underground testing program, in which individual tests cost between $10 and $70 million.

An HEDF-like facility might become very attractive to weapon designers in the US or the Soviet Union if low-yield devices began to look promising and other types of nuclear testing were banned. CTB opponents might also push for the development of a HEDF during a long-term *interim* 1-kiloton

offshoot of the first Particle Beam Fusion Accelerator, PBFA-I, which previously had been used for ICF experiments), each produce 20-terawatt beams (2 x $10^{13}$ watts) for a duration of 30 nanoseconds— more than half a megajoule per shot, and can fire several shots a day. They generate gamma and x-ray spectra, respectively. In addition, more than 100 kilocuries each of cesium-137 and cobalt-60 are stored for gamma irradiation tests at mega-electron-volt (MeV) energies.

* Kidder, "Militarily Significant Yields," p.2.

threshold test-ban treaty (TTBT) leading up to a CTB, as a way of undermining the efficacy of the latter. They might even use the rationale of assessing the threat of third-generation weapons posed by the other side's HEDF. However, neither superpower could hope to keep the existence of such a facility secret for very long, especially if on-site inspections were permitted under a test-ban treaty.

At yields of around 1 kiloton, one can design and test new thermonuclear weapons and enhanced radiation "neutron" bombs, such as the 1-kiloton W79 8-inch artillery shell. Such thermonuclear devices can also be designed in the form of nuclear shaped charges.

The important features of the regime between the "Comprehensive" test-ban threshold of about 100 kilograms and the "seismically unambiguous" threshold of about 1 kiloton* are thus the following. At the low end of this range, some third-generation physics will become more accessible once ICF becomes feasible; in the middle, compact nuclear warheads, which might serve as sources for third-generation weapons, have already been designed; and at the upper end, neutron enhancement and thermonuclear warheads become a real possibility. The potential for a seismically quiet HEDF to disguise nuclear tests up to 0.3 kilotons and the yet unknown applications of subkiloton warheads for certain third-generation concepts (such as NKEWs and microwave devices) makes the significance of this regime difficult to assess. One can only surmise that this range will become more controversial as the technologies advance.

The regime between 1 kiloton and 150 kilotons encompasses most of the nuclear testing that has occurred since the signing of the 1974 TTBT. Within that range, the design of new boosted-fission triggers—probably possible at around 1 kiloton—becomes relatively easy by 10 kilotons.† Since

* The threshold of 1 kiloton is only a representative value from within the range 0.1–10 kilotons and assumes in-country seismic stations. To reliably detect *and identify* decoupled nuclear explosions would probably require a threshold around 5–10 kilotons, whereas fully coupled explosions can at least be *detected* down to 0.1–0.5 kilotons. See US Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties*, OTA-ISC-361 (Washington DC: US Government Printing Office, May 1988), pp.9–14.

† Cf. Frank von Hippel, Harold A. Feiveson, and Christopher E. Paine, "A Low-Threshold Nuclear Test Ban," *International Security*, 12, 2 (Fall 1987), pp.135–151. Boosting involves placing a small amount (a few grams) of deuterium and tritium in the

boosted triggers improve the compactness and efficiency of warheads, boosting would probably be just as important for third-generation devices as it is in current weapons.*

Testing at 150 kilotons is apparently sufficient to certify new warheads with rated yields over 1 megaton. (The B-83 bomb, first deployed in 1984, 10 years after the TTBT, is rated at 1.1 megatons.†) It is not clear, however, if the same would apply to third-generation designs. Some of the more complicated ideas, such as the XRL, may not only *require* large yields to make an efficient device, but may also have scaling laws prohibiting their development without full-yield testing.

In the end, however, it may not be possible completely to design *or* assess the threat of third-generation weapons without atmospheric testing, which is currently banned by the 1963 Limited Test Ban Treaty (LTBT) and politically inconceivable to resume. Most weapon effects from first- and second-generation weapons can in principle be estimated from the known characteristics of blast, radiation, and heat, and, to some extent, from the high-altitude studies of EMP and above-ground explosions conducted before the LTBT. But many directed-energy concepts depend critically on precise aiming and long-range propagation of a narrow beam of energy or particles. Others, like enhanced EMP weapons, might depend on complicated mechanisms of coupling to the atmosphere.

Furthermore, even a crude estimate of a third-generation weapon's effectiveness might be severely inflated unless unforeseeable circumstances in a wartime environment are taken into account. Vibration as the nuclear detonation is triggered, turbulent gases in the path of the beam, radioactivity or a nuclear-disturbed atmosphere—all could contribute to this uncertainty. Because of the large number of unknowns, much of the third-generation effort—whether for threat assessment or for development of the

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core of a fission primary. Under conditions reached in the core, this thermonuclear fuel can ignite, releasing copious neutrons that make the fission process much more efficient.

* Since the trigger in large thermonuclear warheads is predominantly responsible for overall warhead reliability, confidence can be maintained in most of the current arsenal—and new triggers can even be designed (for example, safer ones with insensitive high-explosive)—through testing below about 10 kilotons.

† *Nuclear Weapons Databook, volume 1,* p.200.

weapons themselves—might prove to be futile in the absence of atmospheric and space-testing.

## X-RAY LASERS AND RELATED TECHNOLOGIES

Of the three auxiliary technologies to be discussed, Inertial Confinement Fusion (ICF)* may have the most potential to affect next-generation weapon development. Within the next decade, thermonuclear microexplosions produced by ICF may enable scientists to better understand warhead physics involving x-ray production, implosion dynamics, and instabilities—but only when actual pellets are ignited. Since the most powerful lasers and particle beams currently available for ICF research are still unable to provide more than about 100 kilojoules and 1 megajoule, respectively, in the requisite pulselength, pellet ignition remains a formidable task.† And without being able to ignite at least a few pellets, the design of more *efficient* pellets remains elusive.

However, in its FY 1987 report, the House Science and Technology Committee disclosed that explosions at the Nevada Test Site have provided data for the laser fusion program.‡ In a program called Centurion-Halite, the intense radiation from underground nuclear explosions has apparently been used in attempts to ignite ICF targets, ultimately to help design pellets that could be ignited with *currently available* drivers, thus circumventing the need for a next-generation short-pulse laser at a price of almost

* cf. R. Stephen Craxton et al., "Progress in Laser Fusion," *Scientific American*, **255**, 2 (August 1986), pp.68–79; and Thomas H. Johnson, "Inertial Confinement Fusion: Review and Perspective," *Proceedings of the IEEE*, **72**, 5 (May 1984), pp.548-594.

† Although ignition of ICF pellets does not require nearly as much energy as ignition of thermonuclear reactions in warheads (which need triggers of at least 0.1–1 kiloton, or about $10^{12}$ joules), ICF is still thought to require almost 10 megajoules to achieve the temperature and pressure thresholds required for fusion. Furthermore, this must be delivered in a few nanoseconds to a sphere no more than millimeters in diameter. The two principal nanosecond ICF drivers available today are Livermore's Nova laser, costing around $200 million, and Sandia's upgraded Particle Beam (light-ion) Fusion Accelerator (PBFA II), costing around $50 million.

‡ US Department of Energy, "Civil Energy Programs Authorization Act for FY 1987," House of Representatives Report 99–719, part I.

one billion dollars.*

The connection between ICF and weapon design also extends to third-generation weapons. A National Academy of Sciences review describes the potential for ICF to benefit weapon design as follows:†

> A convenient laboratory source of 1000 MJ thermonuclear explosives would be an *extraordinary tool* for exploring the physics of thermonuclear weapons. Some concepts on how to use nuclear weapons as sources of directed-energy-like *x-ray lasers* or *microwave beams* could be tested in a laboratory setting quickly and interactively.... Extensive experimental campaigns...which would be *prohibitively expensive for underground testing*, could be carried out with an ICF facility. (emphasis added)

The implication here is that once an ICF facility is working, it could provide a crucial research and development tool for such things as nuclear-explosive–powered XRLs and microwave beam weapons, because it might be the only source of testing affordable for the number of tests required.

Even without ICF, however, advanced research on XRL physics is proceeding rapidly. In the laboratory, XRL experiments have demonstrated soft x-ray lasing from selenium foil using optical laser pumping from the Novette laser.‡ Although these experiments remain far from unveiling a ready-made design for a bomb-pumped laser (and, in fact, are performed at wavelengths more than 10 times longer and therefore less energetic than those envisioned for the nuclear-pumped version),§ they cross a dramatic

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* Mark Crawford, "Underground Tests Used in Laser Fusion Effort," *Science*, **233**, 19 September 1986, p.1256; and National Academy of Sciences, "Review of the Department of Energy's Inertial Confinement Fusion Program," William Happer Jr., chairman, (Washington DC: National Academy Press, March, 1986), p.47, 55. Centurion-Halite is operated jointly by the Livermore and Los Alamos National Laboratories, and, although details are classified, it reportedly involves theoretical and experimental collaboration of weapon designers and ICF scientists in a program described as "quite successful."

† NAS "Review of ICF Program," p.35.

‡ M.D. Rosen et al., "Exploding Foil Technique for Achieving Soft X-Ray Laser," pp.106–109, and D.L. Matthews et al., "Demonstration of a Soft X-Ray Amplifier," pp.110–113, *Physical Review Letters*, **54** (14 January 1985).

§ The differences between the laboratory soft x-ray (XUV) laser and the nuclear version are not insignificant. In addition to orders of magnitude differences in output wavelength and power, pumping of the x-ray lasant with visible light is considerably different from that using thermal x-rays from a nuclear explosion. Some lasing in the full-blown version of the x-ray laser was reported as early as 1981 (Clarence A. Robinson, Jr., "Advance Made on High-Energy Laser," *Aviation Week & Space Technology*, 23 February 1981, pp.25–27), and at least five underground tests have occurred over the last six years.

threshold in the design process. They achieve the physical process of lasing in a working, measurable device, allowing scientists to refine the *computer simulation codes* that are ultimately the key to designing real devices.* Moreover, for efficient implosion, the lasant rods used in the *nuclear XRL* may well utilize some of the same complicated configurations, using alternating layers of low– and high–atomic-number and low-density materials,† that are used in ICF pellet designs. For instance, it comes as no surprise that "...the exploding foil target design [in the laboratory XRL] is based on experience with...plasmas that are produced in ICF research...."‡ In figure 1, the close relationship of ICF to nuclear testing and x-ray laser research is shown schematically.

Another technology of particular importance to XRL research and recently developed at Livermore is the Electron Beam Ion Trap (EBIT), a unique device using an electron beam to trap multiply ionized atoms of various metals. By stripping away electrons to achieve a desired charge state in an atom, the EBIT has proven to be of "vital importance in determining the kinetics of hot plasmas."§ Ions can be trapped for up to hours, during which time careful measurements can be made of recombination and collisional excitation cross sections, and x-ray transition energies. These data, already showing extremely "clean" x-ray spectra up to 10 kiloelectron volts (keV) and beyond, are critical for understanding the population inversions and transitions in x-ray lasants. One atom that has already been studied is neon-like (69-times ionized) gold, which was found to produce very sharp x-ray peaks at 9.5 and 10.5 keV.

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Nevertheless, estimates of the number of tests needed to complete the XRL research program range from 30-50 (Hans Bethe, Cornell) to 100–200 (Bob Seldon, Los Alamos). See, for example, *FAS Public Interest Report* (December 1986), p.5–6; and Thomas B. Cochran, et al., *Nuclear Weapons Databook Volume 2*, (Cambridge, Massachusetts: Ballinger, 1987), p.24.

* Two such codes—LASNEX, which simulates the laser-foil interactions involving absorption, burnthrough, and hydrodynamic motion, and XRASER, which simulates the lasing process using detailed atomic spectral data—have been "exercised with great success." Rosen et al., "Exploding Foil Technique," p.106.

† Cf. George Chapline and Lowell Wood, "X-ray Lasers," *Physics Today*, June 1975, p.43, figure 3.

‡ Matthews et al., "Demonstration of Soft X-Ray Amplifier," p.110.

§ "The Electron Beam Ion Trap," *Energy & Technology Review*, August 1988, p.84.

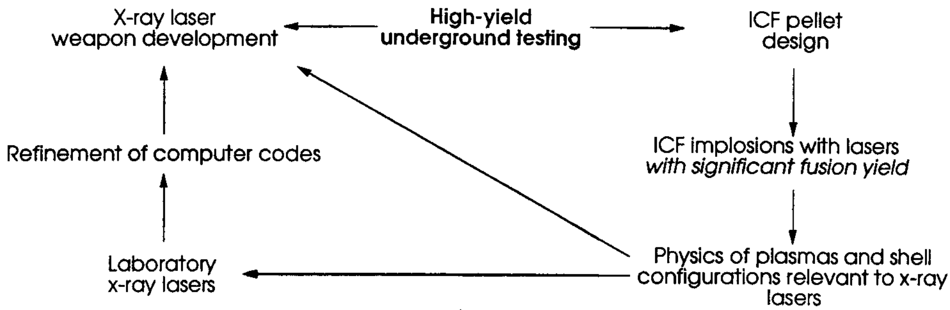


**Figure 1:** Two paths to x-ray lasers from underground testing

However, it will still be nuclear tests—and possibly even large-yield tests—that ultimately determine the fate of the XRL weapon-development program. Not only do underground explosions for ICF pellet design probably require yields well above 1 kiloton,* but the XRL itself may also need high-yield detonations for its source, especially if it is to produce keV x-rays. The need for such large sources of energy derives from the tremendous pumping power required to ionize the atoms' inner electrons at a rate

* Ignition of ICF pellets by this method would probably require high-yield detonations, because it is very difficult to focus more than a tiny fraction of a bomb's radiation onto a pellet no more than millimeters in diameter, especially when the experiment would have to be performed at a distance that allowed diagnostic equipment to be protected—for at least some tens of nanoseconds—from material residues of the detonation.

comparable to the *spontaneous* decay time of x-ray photon emission.[*] This requirement combined with the inefficiency of pumping thin rods, and the fact that x-rays needed for pumping (that is, having energies greater than about 10 keV) can only come from the temperatures reached in a relatively high yield-to-weight nuclear detonation, indicate that large-yield detonations, much greater than 10 kilotons, are probably required to pump an x-ray laser weapon.[†]

The XRL concept is constrained not only by physics, operational uncertainties, and engineering tradeoffs, but also by the 1967 Outer Space Treaty banning nuclear weapons from space.[‡] Nevertheless, research is already being funded to assess target acquisition, tracking, and pointing (ATP) of an XRL *weapon.*[§] Although it is still highly uncertain whether such a device could ever be built, the American Physical Society report on DEWs concludes that "...the x-ray laser, if successfully developed, would constitute a particularly serious threat against space-based assets of a ballistic-missile defense."[¤] For some, the dream of developing an extremely powerful XRL device continues to be a major reason for not supporting a test ban.

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* Cf. Chapline and Wood, "X-ray Lasers," p.42. The time $\tau$ for spontaneous allowed electron energy-level transitions at x-ray wavelengths is approximately $\tau = 10^{-15}\ \lambda^2$ seconds, where the wavelength $\lambda$ is expressed in angstroms. To compete with 1-angstrom (10 keV) transitions requires pumping at 10 keV per $10^{-15}$ seconds, or roughly 1 watt per atom—a flux of energy that, while enormous, *is* achievable with nuclear detonations. For example, 100 kilotons worth of x-rays released in $10^{-9}$ seconds is $4 \times 10^{23}$ watts. Since typical solid densities are about $5 \times 10^{22}$ atoms per cm$^3$, this power would deposit about 1 watt per atom if it were uniformly absorbed by 8 cm$^3$ of solid lasant material. For example, a 65-centimeter long cylinder of diameter 20 centimeters and thickness 20 microns would use 8 cm$^3$ of material.

† See, for example, the technical discussion by Kosta Tsipis, "Third-Generation Nuclear Weapons," *SIPRI Yearbook of World Armaments and Disarmament 1985* (Oxford: Oxford University Press, 1985), pp.97, 103–106.

‡ Strategic and operational shortcomings of XRLs are discussed in a number of references, and will not be further addressed here. See, for example, Ashton B. Carter, *Directed Energy Missile Defense in Space—A Background Paper*, (Washington DC: US Congress, Office of Technology Assessment, OTA-BP-ISC-26, April 1984), pp.24–28, 45–52; and Tsipis, "Third Generation Nuclear Weapons," p.94–98.

§ Theresa M. Foley, "Martin Marietta Selected to Design Potential Nuclear SDI Systems," *Aviation Week & Space Technology*, 10 August 1987, p.113. A $20 million contract was awarded for ATP studies on the XRL along with $11 million for the Prometheus concept, each covering a three-year period.

¤ APS Report, "Directed Energy Weapons," p.S9.

## DIRECTED THERMONUCLEAR EXPLOSIVES

Another device being investigated by both SDI architects and weapon designers is "a kind of nuclear shotgun with little pellets"* named Prometheus. According to a Congressional report that was otherwise quite pessimistic about SDI, Prometheus "may have nearer-term applications for picking out warheads from decoys"† (in the midcourse phase of ballistic-missile flight) than the Neutral Particle Beam (NPB), a leading contender for that role. Encouraged by experiments already conducted, SDI officials in 1987 ordered an acceleration of the Prometheus project for "concept verification," using funds from that year's $500 million supplemental SDI request.

One research engineer familiar with the project described the device as operating much like a rifle, using a polystyrene-filled barrel to help couple a plate to the "gunpowder-like" blast of a directed nuclear charge. After the impulse from the explosion generates an intense shock wave, the plate "fractionates" into millions of tiny particles. Of course, these would vaporize if in direct contact with the bomb, but as configured, the pellets have reportedly achieved speeds of 100 kilometers per second without vaporization.‡

Thermonuclear shaped charges, one of the better understood third-generation concepts,§ have much in common with conventional shaped-charge explosives already used extensively in military and commercial applications. Both conventional and thermonuclear shaped charges tailor an

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* Former SDIO director Lt. Gen. James Abrahamson, quoted in Lemonick, "Third Generation of Nukes," p.36.

† D.C. Waller, and J.T. Bruce, "SDI: Progress and Challenges, Part II," Office of Senators William Proxmire and J. Bennett Johnston, 19 March 1987, pp.25, 39.

‡ SPARTA, Inc., Workshop on Interactive Discrimination, 1986, unclassified. The velocity of 100 kilometers per second falls between the goal of 50 kilometers per second in the 1960s, only a fraction of which was achieved, and the 1,000 kilometers per second velocities possible with the plasma howitzer concept. The latter allegedly operates at 10 percent efficiency up to about 1 megaton, although with only about $10^{-2}$ radian beam directivity. Speeds of 1,000 kilometers per second are inevitably accompanied by ionization, and because charged particles curve in the earth's magnetic field, they would not be useful for long-range applications. Velocities up to 200 kilometers per second, however, are believed possible without vaporization.

§ See, for example, the detailed analysis of nuclear shaped-charges by R. Schall, "Detonation Physics," in P. Caldirola and H. Knoepfel, eds., *Physics of High Energy Density*, (New York: Academic Press, 1971), pp.230–244.

explosive burn-wave using a detonation front that releases energy along a prescribed path. Both can produce jets of molten metal having velocities greatly in excess of the detonation velocity.[*]

For thermonuclear fuels such as deuterium plus tritium, the burn-wave can be directed by placing hollow bubbles or inert solids in the path of the detonation front in order to alter its velocity. Of course, ignition of a thermonuclear burn in a *warhead* requires a fission trigger to achieve the necessary compression and temperature (about 100 million K), but even with such a (nondirected) trigger, the overall directivity of a thermonuclear shaped charge can still be significant.[†]

Velocities achievable with thermonuclear shaped charges are impressive. Unlike molten jets produced by conventional shaped charges, which are limited to about 10 kilometers per second (about four times the velocities of the gases resulting from chemical explosions), thermonuclear shaped charges can in principle propel matter more than two orders of magnitude faster. Since fusion temperatures reach 100 million K, the detonation front of a thermonuclear explosive travels at speeds in excess of 1,000 kilometers per second. Using a convergent conical thermonuclear burn-wave with a suitable liner, one could theoretically create a jet traveling at 10,000 kilometers per second, or 3 percent of the speed of light.[‡]

Up to 5 percent of the energy of a small nuclear device reportedly can be converted into kinetic energy of a plate, presumably by employing some combination of explosive wave-shaping and "gun-barrel" design, and produce

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* Friedwardt Winterberg, *The Physical Principles of Thermonuclear Explosive Devices*, (New York: Fusion Energy Foundation, 1981), p.117. Conventional shaped charges have been applied to demolition, antisubmarine weapons, and advanced ordnance antitank munitions—all being further developed at Livermore—as well as for igniting the fission triggers in thermonuclear warheads. Cf. *Energy & Technology Review*, Lawrence Livermore National Lab, (June–July 1986), pp.14–15.

† Devices based on this principle were pursued in the 1960s. Project Orion examined their potential for space propulsion. Casaba and "nuclear howitzer" were names for weapon applications.

‡ The detonation front shock-wave velocity is $(32\ kT/3M)^{1/2}$, where $M$ is the average mass per ion of the thermonuclear fuel. Suitable geometries can propel matter at many times the detonation front velocity. Using cone geometry, the jet speed is $v/\sin\theta$, where $v$ is the detonation-front velocity and $\theta$ is the cone's half-angle. A practical minimum for $\theta$ has reportedly been found to be $\theta \approx 0.1$. See Winterberg, *Thermonuclear Physics*, p.41, 122.

velocities of 100 kilometers per second and beam angles of $10^{-3}$ radians.* (The Chamita test of 17 August 1985, reportedly accelerated a 1-kilogram tungsten/molybdenum plate to 70 kilometers per second.†) If one chooses to power 10 beams by a single explosion, engaging targets at a range of 2,000 kilometers with a kill energy of 40 kilojoules per pellet (one pellet per square meter), then such a device would require an 8-kiloton explosive and could tolerate random accelerations in the target, such as a maneuvering RV or satellite, of up to 0.5 g (5 m/s$^2$).‡

The initial plate for each beam in this Casaba-like device would weigh only 32 kilograms but would have to fractionate into tiny particles to be an effective weapon—4 million evenly spaced pellets to produce one per square meter at 2,000 kilometers range. If such pellets could be created uniformly, which is highly questionable, then, at a velocity of 100 kilometers per second, they would each weigh 8 milligrams, carry 40 kilojoules of energy (the amount of energy in 10 grams of high explosive), and travel 2,000 kilometers in 20 seconds. Such hypervelocity fragments could easily punch through and vaporize a thin metal plate and could cause structural damage in large soft targets such as satellites and space-based sensors, but they would have little probability of striking a smaller RV, or even disabling it if a collision did occur.§

* SPARTA Workshop, 1986. This scaling presumably holds up to about 50 kilotons but, due to blackbody x-ray emission, decreases to about 1 percent for larger yields.

† Robert S. Norris, Thomas B. Cochran, and William M. Arkin, "Known U.S. Nuclear Tests July 1945 to 31 December 1987," *Nuclear Weapons Databook Working Paper* NWD 86-2, Natural Resources Defense Council, September 1988.

‡ The energy fluence per beam, $E$ in J/m$^2$, is approximately $\eta Y/(N_b R^2 \theta^2)$, where $\eta$ is the fraction of overall yield transferred to the pellets, $Y$ is the bomb yield (1 kiloton is equivalent to $4.2 \times 10^{12}$ joules), $N_b$ is the number of individual beams being driven by one bomb, $R$ is the distance to the target, and $\theta$ is the individual full-beam divergence angle. A maneuvering target could accelerate out of the path of the beam if $a_m R/v_f^2 > \theta$, where $a_m$ is the magnitude of the target's average acceleration, $v_f$ is the particle velocity, and $\tau = R/v_f$ is the particle fly-out time. (For comparison, the average acceleration of ICBMs is about 40 m/s$^2$.) To deliver this energy requires a total mass per beam of $M_b = 2E(R\theta)^2/v_f^2$.

§ For instance, even if an RV were coated with aluminum, a more volatile material than might be expected, the resulting vapor blow-off would only push a 350-kilogram RV off course by about 15 meters in 20 minutes of flight (about five times the amount if there were no ablation), thus failing to degrade significantly the ≈150 meter accuracy of a modern ICBM. Of course, if the collision caused the RV to tumble upon re-entry, the results would be less predictable.

At best, the 8-kiloton 10-beam device in this example would be able to damage 10 soft targets, and at worst it would throw 10 clouds of pellets into space with little probability of damaging anything. The difference, of course, would depend on the pointing accuracy, the uniformity of the distribution of four million pellets, and the availability of timely information about the targets themselves, all posing severe difficulties to a weapon system. Detonation of hundreds of these devices in space might also interfere with target acquisition and communications satellites, thus disrupting critical battle management functions.

The mission being actively considered for such a nuclear cannon, however, is that of a midcourse "sweeper" to help discriminate light decoys from RVs. In table 3 the ASAT and "sweeper" requirements are compared. One SDI architecture study anticipates deploying in space, beginning in the late 1990s, 500 to 2,000 such "Prometheus" devices as a "high-payoff option...[and] technology *required* for interim or far-term missions."* Some analysts have conjectured that such a device could also be configured with a subkiloton nuclear explosive light enough to be deployed in the pop-up mode, thereby avoiding violation of the Outer Space Treaty.

The Prometheus sweeper would utilize the thrust of its nuclear explosion to propel a large dust cloud through thousands of kilometers of space in an effort to discriminate decoys from warheads. The dust would change the momentum of an object by impulsively interacting with its skin. Doppler radars would then distinguish the light objects from the heavy ones by their change in velocity.

As a concrete example, consider a velocity shift of 0.2 meters per second, which is easily detectable with current Doppler-radar technology.† Assuming 5 percent efficiency and a $10^{-3}$-radian beam propagating at 100 kilometers per second, a 10-kiloton warhead could cover 20 square kilometers of area at 5,000 kilometers range using 400 kilograms of dust. The requisite 0.2-meter-per-second velocity shift would then result for decoys weighing up to 5 kilograms whose projected areas were at least

* SPARTA, Inc. "SDI Graceful Evolution Architecture Study," 1986, unclassified. Prometheus devices, in this scheme, would be deployed in the third of seven total deployment stages.

† APS Report, "Directed Energy Weapons," p.S157.

**Table 3:** Estimated values of parameters associated with a hypothetical 10-kiloton nuclear kinetic energy weapon

| | **As ASAT** | **As Sweeper** |
|---|---|---|
| *Number of beams* | 10 | 1 |
| *Mass per plate* | 32 kilograms | 400 kilograms |
| *Mechanism* | 50 kilojoules per pellet *impact kill* | 0.2-meters-per-second velocity change given to target *for radar discrimination* |
| *Assumptions* | $4 \times 10^6$ particles per beam *uniformly spaced 1 per $m^2$ at 2,000 kilometers* | Decoys would be light *mass up to 5 kilograms, with cross-section > 0.5 $m^2$* |
| *Range* | 2,000 kilometers | 5,000 kilometers |
| *Coverage** | Target with random acceleration up to 5 $m/s^2$ | 20 $km^2$ of space |
| *Number needed* | Many | 1 for each ICBM in range 50,000 to sweep entire corridor |

* This assumes a particle velocity of 100 kilometers per second and directivity of $10^{-3}$ radians.

The comparison between the antisatellite and "sweeper" missions is based on a workshop organized by Sparta, Inc., an SDI consulting firm (see text).

0.5 square meters.*

If sufficient tracking radars and battle management computers were in place, and if Prometheus were not attacked directly, this system would theoretically be capable of some amount of midcourse discrimination.

* The actual collision dynamics of hypervelocity grains of dust impinging on thin-walled decoys or heavy RVs is complicated; the momentum transfer can be enhanced several hundred percent if the dust causes substantial vapor blowoff, or it can be diminished if the dust sticks to or pierces the object. Assuming that the dust's momentum is transferred directly to the decoy—that $m_{dust} V_{dust} \approx M_{decoy} \Delta v$, where $m_{dust}$ is the mass of dust striking the decoy, the following relation can be derived:

$$Y\eta = (A_{cov}/A_{decoy})M_{decoy}\lambda v V_{dust}/2$$

where $Y$ and $\eta$ are again the bomb yield and efficiency in creating a jet of dust, $A_{cov}$ is the total area covered by the beam, which is about $(R\theta)^2$, and $\Delta v$ is the change in velocity of the decoy caused by the impinging dust. The total mass in the cloud is then $2Y/V_{dust}^2$.

However, the corridor into which RVs and decoys can be lofted is enormous. Allowing for lofted and depressed trajectories, the objects could fill an area 5,000 kilometers wide (the width of the US) by hundreds of kilometers in height. To sweep this area completely—just once—would require 50,000 ten-kiloton Prometheus devices, and this number cannot be reduced by broadening the beam.

If instead, only one Prometheus device were allocated per enemy missile, it would have to react quickly enough to sweep over all RVs and decoys before they separated by more than a few kilometers from the bus. Achieving such reaction times would be difficult. In the pop-up mode, submarine-launched Prometheus devices would have to be within about 2,000 kilometers of every enemy missile launch point in order for the cluster of RVs and decoys to be no more than 5 kilometers in diameter by the time the dust arrived.* This would be impossible, given that most ICBMs are based far inland. Alternatively, if Prometheus devices were already deployed in space, the absentee ratio would require that at least an order of magnitude more Prometheus devices were stationed in orbit than missiles to be targeted. The likelihood of providing reliable, comprehensive coverage of midcourse trajectories thus remains a monumental task, even if enormous deployments of these nuclear cannons were maintained on hair-trigger alert.

There is also a fundamental problem with both the Casaba and Prometheus concepts that becomes relevant at *higher* yields. Despite the alleged success in directing 5 percent of the energy of a small nuclear explosion into flying debris, a good portion of the remaining energy inevitably becomes blackbody radiation, which would quickly overtake the pellets. Even at 1 kiloton with optimistic assumptions, this poses the risk that most of the particles will be vaporized or even ionized, rendering them

* This assumes that Prometheus would not be fired until the bus was actually seen to be dispensing RVs, and that those RVs would separate at no more than 0.25 kilometers per second: for example, headed for a footprint of 300 kilometers on impact 20 minutes later. (It also assumes Prometheus would be designed with a slightly wider beam for this application—2.5 instead of 1 milliradian.)

ineffective.* The NKEW concept is thus one that may *require* subkiloton explosives to be feasible. If its feasibility also depends on employing *shaped thermonuclear* explosives to help direct the pellets or dust more efficiently, then the concept is further burdened by the difficulty of designing thermonuclear devices with yields less than 1 kiloton. Whatever the case may be, it is clear that demonstrating a rush of hypervelocity pellets from a nuclear blast, while perhaps impressive, in no way guarantees that a useful weapon will ever be derived from this concept.

## ENHANCED MICROWAVE DEVICES

Nuclear weapons designed to produce large pulses of microwave energy with millimeter to meter wavelengths are another important third-generation concept.† Although they have been referred to as enhanced EMP weapons and radio-frequency or microwave weapons, details of these devices are classified, and the extent to which certain ones have been built or tested is not known from the open literature. It is believed that "the realm of advanced technologies includes a directed form of EMP using a high-power microwave beam of immense peak power,"‡ and that both directed and nondirected EMP weapons are being considered.§ In the following, two

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* Even assuming, as is claimed by the SPARTA designers, that the particles can be protected from the bomb radiation for as long as 100 microseconds—after flying 10 meters away at 100 kilometers per second out of a partially shielding "gun barrel," and that 10 percent of a 1-kiloton explosion's energy is released as radiation between that first 100 microseconds and, say, 1 millisecond, the integrated radiation intensity impinging on the pellets during that interval is still 3 kJ/cm$^2$. For 10-milligram particles having a density of 4 g/cm$^3$, the impinging radiation would strike an areal density of 0.4 g/cm$^2$, thus imposing 7 kilojoules per gram on the particles if fully absorbed. Since steel, aluminum, and many other metals vaporize after absorbing as little as 8–15 kilojoules per gram, vaporization would likely become a very serious problem at yields above 1 kiloton.

† Microwave weapons powered by *conventional* sources have also continued to generate interest within the military, and several large secret conferences have been devoted to them. (Cf. Conference Announcement in *Aviation Week & Space Technology*, 3 November 1986, p.151.)

‡ *Nuclear Weapons Databook, volume 1.*

§ Nondirected microwave weapons are called "enhanced EMP" and would probably exploit the coupling of part of a nuclear explosion's radiation to the atmosphere or ionosphere, possibly attempting to extend the range of effects beyond the tangent points to the earth's surface. However, because of the Limited Test Ban Treaty, these devices forms of directed microwave devices are examined, the first of which is shown to be very inefficient. It should be noted, however, that microwaves could be generated by nuclear explosions in a variety of ways, and that other designs, which might require classified information, have not been explored.

## Type I: Electron Plasma Oscillator

One form of directed high-power microwave devices might exploit the principles of System Generated EMP (SGEMP), utilizing the x-rays and gamma rays from a nuclear explosion to produce electron currents and voltage transients in a nearby structure.* To design such a device, one would probably first enhance the prompt gamma radiation by an appropriate configuration and choice of materials in and around the nuclear explosive; for instance, maximizing the gammas produced by inelastic scattering of high-energy (14 MeV) fusion neutrons.† The device could then be surrounded by a cylindrical waveguide structure, possibly built up from many concentric metallic cylinders to serve three purposes: they could act as reflex diodes, emitting an intense pulse of electrons by Compton scattering and the photoelectric effect; they could provide a cavity structure in which the fields could "ring" at a resonant frequency; and they could serve as a microwave horn antenna to direct a beam. Since this diode-waveguide-antenna structure would remain intact for only a very short time before it was blown apart, it would have to exploit the near speed-of-light velocities of the gammas, electrons, and microwaves, to

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could not legally (nor clandestinely) be tested and will not be further discussed here

* cf. L.W. Ricketts, J.E. Bridges, and J. Miletta, *EMP Radiation and Protective Techniques*, (New York: Wiley, 1976), pp.28–29. Gammas and high-energy x-rays cause both forward and backscattered electron emission, which, through a process called Compton charging, can result in internal fields of up to 1 megavolt per meter in satellites. See, for example, Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, third edition, (Washington DC: US Government Printing Office, 1977), pp.521–523.

† In a nuclear explosion, many fission byproducts are created in energetically excited states from which they promptly emit gamma rays. High-energy *fusion* neutrons can also produce gammas by either being absorbed into nonfissioning nuclei (such as nitrogen) or inelastically scattering off of the nuclei of heavier elements. The resultant burst of gammas peaks several tens of nanoseconds after the detonation commences and lasts for only about 10 nanoseconds.

generate a beam quickly.

How powerful might the microwaves from such a device be? Because of diffraction, the intensity of a beam depends not only on the amount of energy produced, but also on its frequency, which depends on the density of the electron plasma. The frequency can be estimated as follows. First, the prompt gammas from a nuclear explosion are generally assumed to carry between 0.1 percent and 0.3 percent of the energy yield.[*] With a judicious design, the prompt gammas available for microwave generation could probably be enhanced to about 1 percent of the overall yield.[†]

Second, since the absorption coefficient (absorption length times density) for 1-MeV gammas is about 40 g/cm$^2$,[‡] a total of a few centimeters of metal in the form of concentric cylinders would suffice to extract most of the energy of the gammas. For each thousand photons or so, one electron (with energy about 0.5 MeV) would be produced.[§] Combining the fraction of the yield released in gammas with the transformation of those gammas into electrons, one can estimate the electron plasma density, whose *natural oscillation frequency* then sets an upper bound on the microwave frequencies attainable.[□]

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* Glasstone and Dolan, *Effects of Nuclear Weapons*, pp.326–327, 340–343. The prompt gamma and neutron radiation generated within the exploding debris during the first few tens of nanoseconds each carry a few percent of the energy yield of an ordinary fission bomb, with neutrons contributing considerably more for thermonuclear devices. Since gammas are largely reabsorbed by the dense expanding debris, the fraction of gammas escaping the explosion is only a few percent of this, but the prompt neutrons partially make up for this second factor by producing additional prompt gammas through scattering and absorption.

† One advantage of using gammas rather than x-rays to produce the electron currents in microwave generators is that, unlike x-rays, which are thermally produced, gammas are created by nuclear processes even at the lower yield-to-weight ratios of low-yield warheads.

‡ Conrad L. Longmire, "On the Electromagnetic Pulse Produced by Nuclear Explosions," *IEEE Transactions on Antennas and Propagation*, AP-26, 1 (January 1978), p.4.

§ Daniel F. Higgins, K.S.H. Lee, and Lennart Martin, "System Generated EMP," *IEEE Transactions on Antennas and Propagation*, AP-26, 1 (January 1978), p.15. Since the electron range in metals is usually much shorter than the gamma photon range, the release of Compton electrons occurs mainly near the metal surfaces and has a typical backscatter efficiency (for 1-MeV gammas) of about $5 \times 10^{-4}$ for aluminum and $2 \times 10^{-3}$ for gold.

□ The electron plasma frequency $f_p$ is approximately 8,980 $n^{1/2}s^{-1}$, where the electron density $n$ is in cm$^{-3}$.

While the 10-nanosecond rise-time of the gamma pulse *by itself* could generate frequencies no higher than about 100 megahertz (and the bulk of that energy, as with high-altitude EMP, would lie in the interval from 0.1 to 10 megahertz), the natural oscillation frequency of the dense electron plasma could produce frequencies several orders of magnitude higher.* Substantial sophistication might be required in order to extract very much *coherent* radiation from such a pulsed sporadic plasma, but a design similar to a virtual cathode oscillator (vircator), for instance, might well produce very intense microwave pulses at frequencies of tens of gigahertz or more.†

Microwaves with high frequencies and thus short wavelengths are extremely desirable for some weapon applications because they can penetrate cracks and couple to smaller conduits in metallic structures. This would be especially important if one were targeting mobile missiles or airborne or ground-based command posts with electronics largely shielded by enclosures. Furthermore, since radio waves below about 10 megahertz are reflected by the ionosphere (which peaks around 300 kilometers altitude and extends from 100 to 1,000 kilometers), higher frequencies would also be needed to target satellites from the ground or to propagate a beam from space downward through this region. In-band damage to most military radars and satellite communications would also require frequencies in the 1–100-gigahertz range. Finally, the strongest reason for higher frequencies is probably just that they make possible narrower beams (given a fixed antenna size) and thus can deliver more *intense* microwaves at the target.

However, since it can be estimated that no more than about $10^{-5}$ of the

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* If we assume an efficiency of 1 electron produced from each 1,000 gamma photons, at most $3 \times 10^{20}$ electrons could be generated by the 1-MeV gamma photons comprising 1 percent of the yield of a 1-kiloton detonation. If these electrons were distributed over a total waveguide volume of a few cubic meters, they would have a density of about $10^{14}/cm^3$ and a natural plasma-oscillation frequency of about 100 gigahertz.

† Vircators utilize the self-electric field of an intense electron beam, typically carrying tens of kiloamperes, to bunch upstream electrons and create an oscillating "virtual cathode." They operate only in pulsed mode, but they are both broadband and tunable, and, unlike gyrotrons, free-electron lasers, and other microwave devices, they neither require bulky magnets nor very high quality beams. Powers of up to 20 gigawatts at 1 gigahertz and frequencies up to 40 gigahertz have been achieved. One particularly high-power vircator called "Gypsy" is already being used by the US Air Force for EMP simulations. See, for example, "Air Force Examines Effects of Microwaves on Electronic Systems," *Aviation Week & Space Technology*, 7 December 1987, p.85.

yield in this kind of device could be transformed into a microwave beam, a 1-kiloton detonation in theory could produce no more than several tens of megajoules of radio-frequency energy.* If we take 30 gigahertz ($\lambda$ = 1 centimeter) as a typical output frequency and assume optics of transverse dimension $D \approx 3$ meters, the microwave beam would diffract into a half-angle of about $1.22\lambda/D \approx 0.004$ radians. The resulting intensity would be no more than about $300/R^2$ J/cm$^2$ at the target, where the target distance $R$ is expressed in kilometers.

Since electronics can be damaged by submicrosecond pulses of microwaves with intensities in the range $10^{-5}$ to $10^{-1}$ J/cm$^2$ and energy in the range $10^{-6}$ joules (for example, microwave diodes) to $10^{-3}$ joules (such as high-power transistors and relays),† a 1-kiloton microwave generator would be relatively useless as a weapon much beyond 300–1,000 kilometers, even if it could be made to work in the manner just described; at most, in might damage *sensitive* electronics or front-end antenna circuitry at ranges well under 1,000 kilometers.

Furthermore, even this relatively small amount of energy might still be too intense to be focused by the device or propagated through the atmosphere, because of electron emission at the device's antenna or microwave breakdown in air. Electron emission occurs at fields around 30 megavolts per meter ($1.2 \times 10^{12}$ W/m$^2$),‡ more than two orders of magnitude below the 40 MJ/($10^{-8}$ sec $\times$ 10 m$^2$) = $4 \times 10^{14}$ W/m$^2$ intensities that the device would have to direct. *Atmospheric* breakdown at radio frequencies

* This assumes 1 percent of the yield is obtained in the form of prompt gammas (where 1 kiloton $\equiv 4.2 \times 10^{12}$ joules), $10^{-3}$ of the gammas produce electrons, and these electrons radiate 100 percent of their energy—an upper bound. Note that about $10^{-6}$–$10^{-5}$ is the fraction of the yield of a high-altitude detonation typically transformed into EMP in the atmosphere. Cf. Longmire, "Nuclear EMP."

† Computer chips fall somewhere in the middle of this range. For pulses shorter than about 100 nanoseconds, the Wunsch damage model predicts junction failure at a certain amount of *energy*, not power, because the heat cannot be dissipated in this short a time. Microwave heating of tissue and skin burns occur only at much higher fluences, in the range 20–100 J/cm$^2$, and melting or cracking of metals requires as much as 1–10 kJ/cm$^2$. Cf. Ricketts et al., *EMP Radiation*, p.76; and Robert J. Antinone, "How to Prevent Circuit Zapping," *IEEE Spectrum*, April 1987, p.37.

‡ For sinusoidal electromagnetic waves whose electric field has magnitude $E$, the average intensity $I$ (in watts per square meter) is given by $I = E^2/2\eta$, where $\eta = (c\varepsilon_0)^{-1}$ = 377 ohms.

occurs after a few nanoseconds at intensities in the range $10^9$–$10^{10}$ W/m$^2$. Thus if the device were aiming into the atmosphere from an altitude less than about 200 kilometers, no more than the first small fraction of a 10-nanosecond pulse carrying the microwave energy would propagate.

## Type II: Magnetic Flux Compressor

Another design, however, may hold more promise. As early as 1983 at Sandia National Lab, research in the area of *conventionally* powered "explosive magnetic-flux compressors" was producing 2-megajoule pulses of magnetic energy with peak voltage-current products of 0.2 terawatts. Since then, this has been increased to 18 megajoules. These power levels are accomplished by successively staging three explosive generators in series, each feeding an intense current pulse into the next. Each stage detonates an explosive charge inside a metallic cylinder that is enclosed by a rigid current-carrying solenoid (see figure 2). The magnetic flux in the gap between the cylinder and the solenoid is then explosively compressed as the cylinder expands, working against the already established (and increasing) magnetic pressure. Some of the energy of the explosion is thus transformed into a sharply rising current pulse (inversely proportional to the area containing the flux) that can be fed into an antenna to form an intense electromagnetic pulse.[*]

A nuclear version of such a device might be able to produce a much faster rising current pulse and an immense peak power.[†] Even with the conventional version, exponentially rising current pulses peaking at over 10 mega-amperes and having 10-microsecond rise-times have been achieved, and 10 percent–20 percent energy conversion has been demonstrated. The

* E.C. Cnare, R.J. Kaye, and M. Cowan, "A 2 MJ Staged Explosive Generator," in M.F. Rose and T.H. Martin, eds., *Proceedings of the 4th IEEE Pulse Power Conference*, Albuquerque, NM, 6–8 June 1983, pp.102–104. The device is no more than a few cubic meters in overall volume, including the initial power supply and the antenna structure.

† At the relativistic liner speeds possible with nuclear explosions, *direct* transformation of magnetic flux into electromagnetic waves "squirting out the end" of a solenoid is also a theoretically efficient possibility. This would require a shaped-charge to start the solenoid compression at one end, but fields of up to $10^{11}$ gauss are thought possible. Cf. H.E. Wilhelm, "Initial-Boundary-Value Problems for Magnetic Flux Compressors," in *IEEE Pulsed Power Conference Proceedings*, p.112; and Winterberg, p.123.

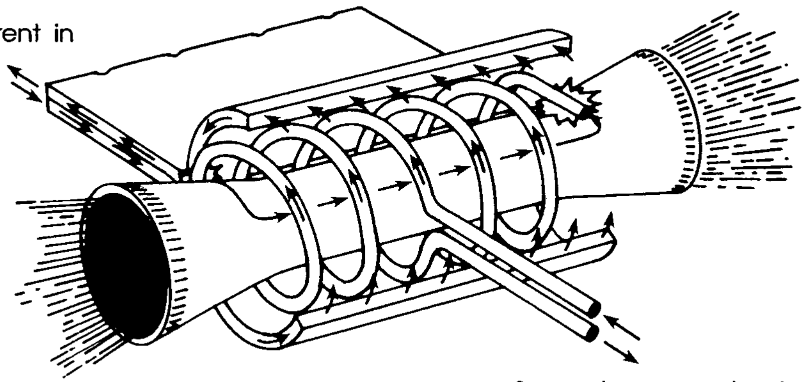


**Figure 2:** Schematic diagram of a conventionally powered magnetic-flux compressor. The cylindrical armature expands as it generates a current pulse in the surrounding coil. Source: E.C. Cnare et al., p.102. Figure © IEEE 1983.

corresponding time-scale for flux compression using a nuclear detonation would be in the nanosecond range,* resulting in current pulses of extremely narrow duration. If a suitable winding scheme could be devised for the solenoid and antenna feed wires,† a lightweight generator could be envisioned whose largest components might be the batteries used to initiate the solenoid current, and the antenna itself. The latter might be a stripline structure similar to that used in the conventional device, or possibly an

* Thermonuclear detonation fronts traveling at 1,000 kilometers per second or more conceivably could compress the last fraction of a centimeter of flux in well under 10 nanoseconds.

† The conventional device uses a clever branching scheme for the solenoid windings such that the current density per turn remains about constant as the explosion and rising current proceeds down the solenoid. See Cnare et al., p.102. The nuclear version might further be limited by the strength of the coils themselves to withstand the increasing magnetic pressure, $B^2/8\pi$ in cgs-gaussian units, or $B^2/2\mu_0$ in MKS. However, since the nanosecond time-scales are so much shorter than the magnetic diffusion time $\tau \approx d^2\mu_0\sigma/2$, which is about 40 microseconds for $d = 1$ millimeter of copper with conductivity $\sigma = 5.8 \times 10^7$ siemens per meter, nearly perfect trapping of the flux can be assumed as long as the solenoid is intact.

*array* of antenna elements to increase the directivity.

It is conceivable that the efficiency of such a microwave device could be much higher than the other nuclear design discussed above. If 5 percent of the total yield of a small nuclear explosion could be transformed into kinetic energy of an expanding cylindrical armature, similar to the kinetic efficiency claimed in the Prometheus device, and if the solenoid structure remained intact long enough to transform a substantial fraction, perhaps a few percent, of that energy into a current pulse, then efficiencies (from bomb yield to electromagnetic energy) of order $10^{-3}$ might be possible,* as opposed to $10^{-5}$ for the other hypothetical nuclear-powered microwave device discussed above. Furthermore, if subnanosecond rise-times could be achieved, atmospheric breakdown might be largely averted.

However, there remains the difficult problem of designing an antenna to effectively transform such an intense current pulse into a microwave beam. Even using an array of half-wave dipole antennas, one is still limited by diffraction to beamwidths of order $2\pi c\tau/D$, where $c$ is the speed of light, $\tau$ is the pulsewidth in seconds, and $D$ is the overall size of the array. Unless pulses much *shorter* than 1 nanosecond could be achieved, the resulting wavelengths of tens of centimeters would require enormous structures (hundreds of meters) to achieve milliradian divergences. For a pop-up weapon or one to be used within the atmosphere, such sizes would be impractical. Compared to the other nuclear microwave device, this design might lose in directivity what it gained in efficiency, thus also lacking the capability of assured lethality over large distances.

## Mission-oriented Considerations

Nevertheless, using microwaves generated from a 1-kiloton device at 200 kilometers altitude to damage at least unprotected electronics over an

* The efficiency of the nuclear version of the explosive flux generator here is estimated to be substantially less (perhaps as much as two orders of magnitudes less) than the *conventional* version for the following reasons: the higher temperatures of nuclear explosions produce blackbody radiation and are thus less efficient at producing pure kinetic energy, and the strength of the solenoidal structure ultimately limits the amount of kinetic energy that can be transformed into current. These factors also suggest, however, that the nuclear efficiency might go up substantially as the yield is decreased.

**Table 4:** Hypothetical microwave devices compared to EMP*

Author's estimates of the characteristics of two hypothetical microwave devices of the types discussed in the text. For perspective, the microwave outputs from 1-kiloton devices detonated at 100 kilometers altitude are compared to the electromagnetic pulse of a 1-megaton explosion at the same height. If the postulated directivities could be achieved, the 1-kiloton devices might be able to deliver significantly more energy to their limited areas than the 1-megaton (nondirected) explosion. Serious questions remain, however, over the design and microwave-propagation characteristics of such devices.

| | **Microwave device**† *1 kiloton* **Type I** | **Type II** | **Normal EMP** *1 megaton* |
|---|---|---|---|
| *Frequency* | Tens of gigahertz (?) | Single pulse *gigahertz range* | Single pulse *megahertz range* |
| *Efficiency* | $< 10^{-5}$ of yield | $\approx 10^{-3}$ of yield | $\approx 10^{-6}$ of yield |
| *Directivity* | $10^{-3}$–$10^{-1}$ radians | $\approx 10^{-1}$ radians | Tangent point to earth's atmosphere at 30 kilometers altitude |
| *Coverage (diameter)* | 0.1–10 kilometers | $\approx$10 kilometers | 2,000 kilometers (30 percent of US land area) |
| *Energy flux (at the earth)* | $5 \times 10^{-1}$–$5 \times 10^{-5}$ J/cm$^2$ | $\approx 5 \times 10^{-3}$ J/cm$^2$ | $10^{-7}$ J/cm$^2$ |

* each assumed to be detonated at 100 kilometers altitude.

† Type I refers to the hypothetical design based on a gamma-ray-induced electron plasma, somewhat analogous to a virtual cathode oscillator. Type II involves an explosively generated current pulse and is based on magnetic flux compression.

area of several square kilometers might seem appealing to some.* As summarized in table 4, the electromagnetic flux over a select area from either of these two devices could be several orders of magnitude higher

* In contrast, the normal EMP intensity from a 1-megaton detonation at 200 kilometers altitude would average only about $10^{-7}$ to $10^{-6}$ J/cm$^2$ and would indiscriminately affect an area nearly half as large as the US, with spurious signals varying greatly from region to region. This would hardly fit the description of a tightly controlled or so-called "surgical" nuclear strike.

than that of a high-altitude EMP using an explosion 1,000 times larger. During a "limited" nuclear war this might appear to offer the capability of selectively disabling key launch control facilities without causing substantial collateral damage or civilian deaths.* For instance, one of the often stated missions for a microwave weapon is to "hold relocatable targets at risk."† Since nearly 50 percent of the missiles and 25 percent of the warheads in the Soviet ICBM force may be deployed in the mobile SS-24 and SS-25 by the mid-1990s,‡ new ways of threatening such targets—especially if "prompt"—continue to be of interest to counterforce planners.

While the savings in weight over most conventionally powered microwave weapons could be great, conventional alternatives do exist, especially for close-range targets such as ship-based or airborne radars and electronics. Klystrons, gyrotrons, and vircators, which generate high-power pulsed microwave beams ranging from a fraction to tens of gigahertz in frequency, and from several megawatts in continuous-wave to tens of gigawatts in pulsed devices, are already mature.§ Although none of these can deliver more than about 10 kilojoules per pulse (several orders of magnitude less than the hypothetical nuclear devices described above), most can be pulsed repeatedly in rapid succession without being destroyed in the process.¤

Nevertheless, it is hard to imagine any missions for which a microwave generator's "soft kill" capabilities were militarily adequate. For one thing, electronic kill, by its very nature, is hard to observe. In order to protect

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* A wide range of views on the desirability, strategy, and consequences of so-called "limited nuclear wars" can be found in the following articles: Colin S. Gray and Keith Payne, "Victory is Possible," *Foreign Policy*, Summer 1980, pp.14–27; Ashton B. Carter, John D. Steinbruner, and Charles A. Zraket, eds., *Managing Nuclear Operations*, (Washington DC: Brookings Institution, 1987), pp.3–4, 11, 151–152, 198–204; and William Daugherty, Barbara Levi, and Frank von Hippel, "Consequences of 'Limited' Nuclear Attacks on the U.S.," *International Security*, **10**, 4 (Spring 1986), pp.3–45.

† *Energy and Technology Review*, September 1986, p.4.

‡ *Soviet Military Power 1989*, US Dept. of Defense, (Washington DC: US Government Printing Office, 1989), p.45.

§ H. Keith Florig, "The Future Battlefield: A Blast of Gigawatts?", *IEEE Spectrum*, **25**, 3 (March 1988), p.52.

¤ See, for example, V.L. Granatstein, "High Power and High Peak Power Gyrotrons: Present and Future Prospects," *International Journal of Electronics*, **57**, 6 (June 1986), pp.787–799.

military targets from harmful electromagnetic pulses, the US—and presumably the Soviet Union as well—already employ shielding techniques and surge-arresting circuitry, as well as fiber optics and specially hardened semiconductor materials for critical communication links and command and control. While the costs of implementing these techniques may sometimes be high, the survivability of important circuitry can be increased by many orders of magnitude and then tested with conventional EMP simulators—all in secret from the other side.

Long-range missions such as ballistic-missile defense are essentially precluded by the unavoidable diffraction at microwave wavelengths, and the ASAT role could much more easily be accomplished with direct-ascent homing rockets or even conventionally powered lasers. For battlefield use or for air defense, the drawbacks of nuclear-powered microwave devices are the same as those of the neutron bomb; despite a possible high degree of lethality against front-end antenna circuitry and communications equipment from distances of tens of kilometers, there is still a risk of collateral damage from the residual blast and escalation to all-out nuclear warfare after relegating control of such nuclear weapons to field commanders. Moreover, as a first act of war, when electronic disruption would be most effective, a microwave weapon's nuclear detonation would be highly escalatory. Destroying targets with nuclear-generated microwaves is thus so fraught with uncertainties that it may *never* be considered a reliable means for carrying out military objectives, especially those that weigh heavily in the balance of nuclear war.

Despite their lacking a realistic mission, however, the high-tech attraction of microwave generators may still prove sufficient to secure funding for some time. Although the underlying principles in some cases might be as complicated as free-electron lasers, to which thousands of person-years of development effort have already been devoted, certain designs could also turn out to be quite simple, as in the second device discussed above. Moreover, preliminary research might be possible with currently available non-nuclear generators or, should it become available, with ICF. Once the basic principles are understood, it may then even be possible to test prototypes at nuclear yields well below 1 kiloton. On the other hand, extensive testing might also accomplish little more than to reveal the inherent difficulties of applying such concepts to an actual weapon design, as it has done with the XRL. Nuclear-driven microwave devices might thus end up being pursued more for their charm than for any sound strategic reason.

## CONCLUSION: THRESHOLDS AND TIMING OF TEST-BAN REGIMES

Upon close examination, most third-generation concepts are found to be encumbered by technical uncertainties and operational risks that severely detract from any military utility they might otherwise have. Despite the existence of innovative ideas such as propelling massive dust clouds in space or generating intense beams of microwaves or x-rays, the capabilities of these devices are not likely to be so threatening as to warrant being either greatly feared or greatly coveted. The difference between third-generation *concepts* and useful third-generation *weapons* is immense.

Nevertheless, there is a serious possibility that third-generation "devices" will continue to be pursued, rationalized in the US by the desire to assess the Soviet threat, or due to the technological momentum generated by SDI. The resulting danger is that of an arms race that could undermine not only the possibility of a test ban, but *other* significant arms-control measures as well, particularly limits on destabilizing ASAT weaponry and ballistic-missile defense deployments.

So far, third-generation progress seems to be limited to enhancement of radiation already present in nuclear detonations (as was done for the neutron bomb), a few nuclear tests demonstrating the potential for x-ray lasing in nuclear-pumped plasmas, shattering and propelling a plate in the NKEW concept, and some ideas and possibly tests that adapt known principles (such as System Generated EMP or explosive flux generation) to the design of a directed microwave beam. Other ideas have also been discussed from time to time, such as underground laboratories that would use nuclear explosions to generate stockpiles of radiological warfare agents,*

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* William R. van Cleave and S.T. Cohen, *Nuclear Weapons, Policies, and the Test-Ban Issue* (New York: Praeger, 1986), p.72.

or pure-fusion "clean" weapons and "mini nukes,"* but aside from a few enthusiasts, these concepts have had very little support.

The most propitious circumstances for negotiating a test ban exist when the possibility of developing new weapons appears to be either uninteresting, remote, or both. Fortunately, despite the billion dollars spent by the US on NDEWs over the last few years, third-generation weapons have not yet demonstrated the breakthroughs nor have they created the broad-based enthusiasm needed to place them irreversibly on the political agenda. Nevertheless, this condition is not likely to endure forever, especially given the allure of ICF's experimental utility, the facilities at the Simulation Test Laboratory, computer code development and laboratory x-ray lasers, and auxiliary technologies (such as the Electron Beam Ion Trap at Livermore) for accelerating the development of new concepts. While the significance of either side's developing new nuclear weapon concepts is often exaggerated, these exaggerations have been quite successful at undermining test-ban negotiations. With respect to *low-yield* test bans and third-generation weapons, these arguments can only become more impassioned with time.

The *timing* of test-ban regimes is thus probably much more important for curbing a third-generation arms race than an absolutely foolproof verification at the start. With a low-threshold test ban (even one that includes a small quota for higher yields) there is simply no real possibility for quick or dramatic breakthroughs to pose a significant military threat. Nuclear-pumped XRL and ICF pellet development studies will both probably continue to require testing at yields above 10 kilotons for some time. Others concepts may have difficulties even at lower yields, such as particle vaporization in a NKEW or atmospheric breakdown for an intense microwave beam. Many are so complicated that they may require years of research and dozens of tests to make much progress at all. A case in point would be a microwave device that employed gamma-ray enhancement and coherent plasma oscillations. The phenomena used there are as complex as

* Edward Teller extolled the virtues of fallout-free and very-small-yield tactical weapons more than 25 years ago, yet they have never been demonstrated. See, for example, his article "The Case for Continuing Nuclear Tests," first published around 1961 and reprinted as appendix 64 of the Test-Ban Hearings of 1985, "Proposals to Ban Nuclear Testing," pp.331–6.

those used both in the neutron bomb and in free-electron lasers, and could not be weaponized short of an extensive and lengthy development period.

Nevertheless, with continued funding, in about 5–10 years one might expect ICF ignition in the laboratory, development of a Prometheus-like device, and even a rudimentary microwave device, perhaps having used ICF as a "tool" in the design process. XRLs, even for the easier ASAT mission, as well as the High Energy Density Facility and most other third-generation concepts, would probably take 10–20 years or more. Long before then, however, fears of falling behind in a third-generation arms race could emerge, fueled by early proof-of-principle demonstrations. Charges of a "microwave gap" or other third-generation gaps might soon follow.

If a 1-kiloton threshold were put into effect immediately, technologies such as Prometheus, microwave devices, and ICF would probably be delayed by at least 5–10 years, while XRLs and other third-generation concepts might well be abandoned or relegated to the level of basic computer simulations, non-nuclear physics experiments, or theoretical studies. During a long-term 1-kiloton threshold ban, however, the HEDF might become *more* attractive to those who wanted to keep secret the number of low-yield tests or who wanted to show that the other side might employ the technology to cheat on a future CTB.

Under a *comprehensive* test ban, the ICF program would probably be touted as a way of retaining a cadre of scientists with expertise in weapon physics, as well as a tool for nuclear effects testing. Without high-yield (underground) tests, however, ICF alone would not suffice for third-generation development.

In 20 years then (say, by the year 2010), the strategic outlook resulting from having continued to test up to 150 kilotons throughout the 1990s and then agreeing to a 1-kiloton TTBT in the year 2000 might look significantly different from one in which a CTB had been negotiated in 1990. If testing up to 150 kilotons continues though the 1990s, there will inevitably be a competition between improving seismic verification and developing significant nuclear innovations at low-yield, with the winner as yet undetermined. Further progress in auxiliary technologies such as the STL, laboratory x-ray laser research (including the Electron Beam Ion Trap), the HEDF, and ICF—the first two being already well advanced and the last two within reach in the 1990s—will also likely accelerate weapon development, exacerbate the arguments about CTB verification, and lessen confidence in the effectiveness of any test-ban regime for preventing new types of weapon. Furthermore, rationales involving either the countering of mobile missiles, midcourse discrimination for ballistic-missile defense, or ASAT capabilities may continue to proliferate. With just the 150-kiloton limit on testing, third-generation weaponry might become entwined into the 1990s nuclear arms race in a way that could become difficult to unravel.

But, with either a 1-kiloton TTBT or a CTB *put into effect soon*, the incentives and technical capabilities for third-generation development would be undermined, and the detectability of low-yield testing would likely continue to improve, especially given the opportunities at hand for in-country stationing of instruments and on-site inspections. Although an early test ban might not be a perfect cure, it is probably the best preventive medicine against a third-generation arms race.

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