

DEBATE ON APS DIRECTED-ENERGY WEAPONS STUDY

Is it unduly pessimistic to conclude that it would take a decade or more of intensive research just to determine the feasibility of shielding the US with a system of high-intensity laser and energetic particle beam weapons?

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In April, The American Physical Society issued a 424-page report saying that "even in the best of circumstances, a decade or more of intensive research would be required to provide the technical knowledge needed for an informed decision about the potential effectiveness and survivability of directed-energy weapon systems." (See PHYSICS TODAY, May 1987, page S1.) In May, Los Alamos National Laboratory published a 70-page paper by Gregory Canavan that is optimistic about a directed-energy weapons system and critical of the APS study. (See PHYSICS TODAY, June, page 43.) In this debate Canavan criticizes the APS study on ten technical issues, and Nicolaas Bloembergen and Kumar Patel, the cochairmen of the APS study group, respond point by point.

PHYSICS TODAY wrote brief introductions to each of the ten issues after receiving the manuscripts from both sides in the debate. These introductions appear in italics.

The debaters make frequent reference to the following documents:

▷ *The 424-page APS report. This report, which was published with some modifications as a supplement to the July issue of Reviews of Modern Physics, is reference 1 in the debate.*

▷ *Canavan's 70-page response to the APS study, and a shorter response to the APS study by Lowell Wood (Lawrence Livermore National Laboratory) and Canavan. These two documents, titled Directed Energy Concepts for*

Strategic Defense (or Concepts for short) and Analysis of the APS Report, respectively, are reference 2 in the debate. ▷ The APS study group's response to the critiques by Wood and Canavan. This is reference 3 in the debate.

Opening statements

Canavan: The document *Directed Energy Concepts for Strategic Defense*² provides a context for evaluating the role of directed-energy weapons in strategic defense. *Concepts* was written as an independent and objective evaluation of the role of directed energy in strategic defense. *Concepts* identifies a number of inconsistencies in The American Physical Society's report.¹ Ten of those inconsistencies were developed into issues by the APS study group and transmitted to Congress in June.³ Congressman Curt Weldon of Pennsylvania and 50 of his colleagues requested that I respond to those issues, and my paragraphs below are substantially those sent to Congress. APS selected the ten issues and publicized them in the process of criticizing my paper.

Bloembergen and Patel: We appreciate the opportunity offered us by *PHYSICS TODAY* to respond to the material presented here by Gregory Canavan. Our complete response³ to Wood and Canavan's initial critique² of the APS study¹ is available in preprint form from APS.

Chemical laser power

Chemical lasers emit continuous beams of infrared radiation, which is generated by the mixing of steady streams of reactive gases such as hydrogen and fluorine. Is the APS report correct when it says that ground-based chemical lasers would have to produce powers of 20 MW if their beams, after redirection by orbiting mirrors, are to structurally disable missiles in the boost phase?

Canavan: The executive summary at the beginning of the APS report states that chemical lasers require power

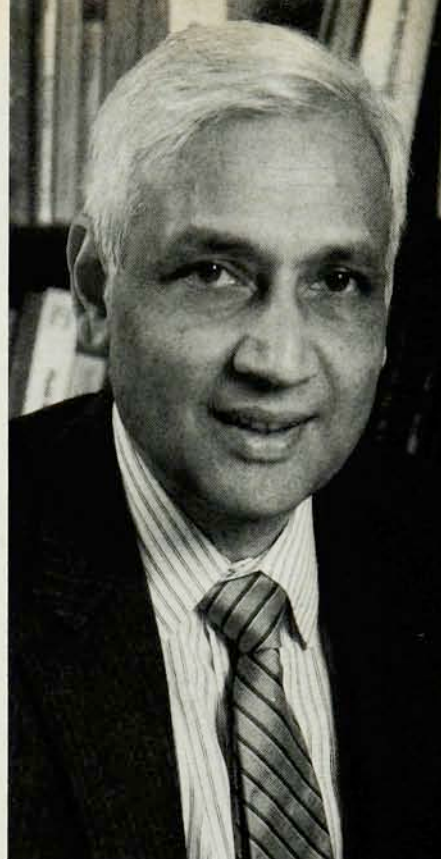
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levels "increased further by at least two orders of magnitude," but the body of the report acknowledges "measured power in excess of 1 MW" (section 3.2.2), so *Concepts* observes that the increase is "one order of magnitude rather than two" (page 16). The APS response acknowledges that "the APS report erroneously states its first conclusion of its executive summary... Wood and Canavan are correct." The Strategic Defense Initiative Organization has stated that it commented on classification only, and that content and editing were APS's responsibility alone.

Bloembergen and Patel: The currently demonstrated power levels of the MIRACL chemical laser as stated by Canavan are correct. However, as reference 3 explains, the demonstrated power levels for the hydrogen fluoride-deuterium fluoride chemical lasers, and therefore the needed improvements, were inconsistently stated in the preprint version of the APS report because the Strategic Defense Initiative Organization's classification requirements changed in the seven-month period during which the classification review took place. The clerical error has been corrected in the *Reviews of Modern Physics* version of the APS report. Furthermore, Wood and Canavan's many inferences in reference 2 that this error was deliberate are incorrect. The needed improvement in the HF-DF laser output is a factor of 20. More importantly, as the APS report makes amply clear in section 3.2.2, the laser that achieved the best performance (the laser referred to both in the APS report and in Wood and Canavan's response²) cannot be scaled to significantly higher powers. Thus, the true measure of scaling must start from a different chemical laser design, and no such design has yet been demonstrated.

Chemical laser scaling

Orbiting chemical lasers, too, could potentially destroy

missiles in the boost phase. How close are today's lasers to having the required power, and how many laser satellites would be needed?

Canavan: The APS response only changes the *Reviews of Modern Physics* article to say that power must be "increased by at least an order of magnitude" (page 1), but *Concepts* showed that such an increase is not necessary for useful applications (pages 9–10). The *Analysis of the APS Report*² notes that the APS report's "current" power levels are "within a factor of 3 of the beam power needed" (page E2006). The analysis in the APS report supports the factor of 3 (appendix B). *Concepts* shows on page 9 that in early, low constellations the number N of satellites would scale as about $1/B^{1/2}$ with laser brightness B . If a satellite's mass is proportional to its brightness, the constellation's mass and cost would then scale as NB , or $B^{1/2}$, and smaller lasers would be preferred. The exact solution⁴ changes the details, but not the general observation that smaller lasers can be useful as well as less sensitive to the APS's "short ranges [and] rapid retargeting."³

Bloembergen and Patel: Reference 2 states that current chemical laser power levels on the ground are within a factor of 3 of those needed to oppose current threats. Conclusion 1 in the APS report is for power levels needed in space to meet realistic future threats, as the body of the report makes abundantly clear. Even against the current threat, Wood and Canavan's analysis includes a number of assumptions and judgments favorable to the defense's satellites, such as short ranges, rapid retargeting, high beam quality, low losses and very effective lethality. None of these is close to being demonstrated at scale. Canavan specifically argues that large numbers of low-power, low-altitude satellites will suffice, but this design would maximize the constellation's survivability problems, as we mention below.

Satellite constellations

What restrictions on the defense arise from the relationships among the ranges of orbiting weapons, their altitudes in space and the locations of their intended targets?

Canavan: The "standard reference"⁵ on satellite constellation scaling cited by the APS response is derived from earlier work,⁶ as the response acknowledges. The APS study group derives its analysis from that reference, but makes unreliable predictions of sensitivities. A useful discussion of constellation scaling and sensitivity requires the exact solution, but even the APS report's approximate analysis indicates that modest lasers are effective. The APS response questions the 1000-km range used in an illustration in reference 6, but that is about the properly averaged range for nominal threats and lasers, as confirmed by standard analyses and the analysis in the APS report. A satellite over the launch area is responsible for the missiles in a zone of radius R equal to $2R_E/(zN)^{1/2}$, where R_E is the Earth's radius and N is the number of satellites; the constellation concentration⁵ z is about 3. For 100 satellites, the zone radius is 740 km, which is reduced to 520 km by averaging over the range to targets.⁶ For a typical constellation altitude of 500 km, that gives an average range of 720 km, which is less than 1000 km, even neglecting the shortening of the range as the boosters climb. In the more exact calculation the interpretation is more subtle, but the results are similar.⁴ Other departures from ideality reduce the spacing, so the APS's "range of 2000 km, the value most commonly mentioned in presentations to the study group," either applies to lesser threats, for which smaller numbers of lasers would suffice, or is inconsistent with the APS study.

Bloembergen and Patel: It is straightforward to lower the requirements on laser power by decreasing the operating range and increasing the number of platforms. Mirror platforms, however, cannot be positioned in low Earth orbit, say at 300-km altitude, because their survivability would be a serious issue. The minimum plausible constellation altitude, as section B.1.1 of our report correctly states,¹ is about 500 km, corresponding to ranges of about 1000 km. A "typical" constellation altitude, from the majority of the presentations made to our study group, is about 1000 km, with ranges corresponding to about 2000 km. Our previous response³ stands.

ICBM shielding

Attacking missiles could be shielded to protect them from directed-energy weapons, but at what cost in payload?

Canavan: *Concepts* states that "the uniform hardening of all stages would require that material be added in proportion to their areas rather than their masses" (page 30). The APS response states that "Canavan's computation is correct within the bounds of that assumption," but states that the APS report gives "a general methodology... keeping in mind the fundamental purpose of the group's work as a tutorial" and questioning whether "apportioning shielding by stage area is self-evidently the option that would be chosen by the Soviets." *Concepts* notes that under "the [APS] report's prescription the first stage would be harder than the upper stages, which would leave the upper stages, the ones most susceptible to attack, relatively unhardened" (page 30), the error of which is self-evident.

The literature contains idealized discussions of shielding only the first stage, the second, the bus or combinations. The first corresponds to the case treated in the APS report; the second cannot be justified operationally either.⁷ Lasers can deliver lethal energies to the cloud tops, so leaving the first stage unhardened would gratu-

itously reduce the defense's requirements by an order of magnitude. Uniform hardening requires about twice the payload penalties given in the APS report—5 to 10 of the 10 reentry vehicles carried. Thus "hardened missiles should probably be regarded as carrying only 30–50% of the current number of reentry vehicles" (*Concepts*, page 33). Because the APS report's calculation is irrelevant to the cases of interest, is misleading by a factor of two or more on payload penalties, and is neither simpler nor more general than that in *Concepts*, there is no reason why the APS report's tutorial should not be replaced by the admittedly correct calculation in *Concepts*.

Bloembergen and Patel: As stated previously,³ the weight penalty of shielding was illustrated for tutorial purposes in our report by two limiting cases, which require the least amount of algebra. Canavan's computation is correct for uniform hardening if the total shielding mass is fixed at 6 metric tons. Because our discussion of required laser powers throughout^{1,3} has been based on a nominal hardening with 1 g/cm^2 of ablative material, the logical boundary condition is that no segment should have less than this amount. Using the model rocket geometry of Canavan, one finds that the total shielding mass for uniform shielding is now only 3 tons. Missiles hardened in this manner could carry 60–70% of the current number of reentry vehicles, rather than the 30–50% Canavan calculates on the basis of 2 g/cm^2 of uniform hardening. Note that our example¹ with shielding proportional to the mass of each stage and a total shielding mass of 6 tons still leaves about 1 g/cm^2 on the upper stage and bus and about 5 tons on the first stage. This example, from section 2.3.2 of the APS report, illustrates how much less the payload penalty is due to shielding on the first stage compared with Canavan's estimate.

Even the opposite example of no shielding at all on the first stage cannot be dismissed by Canavan's simple statement that this "would gratuitously reduce the defense's requirements by an order of magnitude." If the burnout altitude of the first stage is below 40 km, and if the defense's lasers are repetitively pulsed excimer or free-electron lasers, then according to the analysis of stimulated Raman scattering on the downlink (section 5.4.9.3 of the APS report), it may be impossible to achieve the focal spot sizes indicated by Wood and Canavan. In conclusion, a nominal uniform hardening of 1 g/cm^2 is achievable with much smaller reentry vehicle penalties than Wood and Canavan state.² The tutorial examples of reference 1 fairly illustrate these penalties for any distribution of shielding between the first and second stages.

Spinning boosters

It is more difficult to destroy a missile by laser beam heating if it is rotating, but what are the necessary rotation rates, and are they practical?

Canavan: The APS report states that "rotations of missiles at angular rates of the order of 1 rps have been studied and shown to extract little or no penalty to the offense" (section 2.3.2). *Concepts* calculates that "missiles would have to rotate at least once per second to have any impact" (page 34), so the upper limit of the rotation rates studied is the minimum required to have any impact. The APS response does not disagree; it only states that "whether it would be practical to accomplish booster rotation by retrofit depends on detailed design features"—the point made by *Concepts*.

Bloembergen and Patel: Wood and Canavan's initial critique is now missing from Canavan's argument. Their objections based on 10-rps booster rotation have no bearing on the 1-rps rotation discussed in the APS report; 1-rps rotation would increase the required kill threshold power for cw lasers, as stated in the APS report. Also,

Canavan is incorrect in stating that the initial APS response agrees with his initial statement that 1-rps rotation is impractical.

Fast-burn boosters

A missile that burns its fuel very rapidly can separate from its weapons bus earlier and at a lower altitude. What impact would this technology have on the defense?

Canavan: *Concepts* does not state, as the APS response suggests, that the APS report "inconsistently rules out neutral particle beams... as boost-phase kill mechanisms" (reference 3, page 5). *Concepts* observes only that "the early Soviet and Union of Concerned Scientists reports on SDI erroneously concluded that neutral particle beams could not propagate below 200–300 km" (footnote, page 25), an observation no one challenges. Buses are not intrinsically harder than missiles—in fact, they may be softer because they must open up to deploy reentry vehicles. The APS response's main point, on which there is strong agreement, is that "destroying [the bus] would indeed still provide the leverage of destroying many reentry vehicles at once" (page 6)—a key point missed by Soviet, UCS and Office of Technology Assessment reports, which assumed that buses became invulnerable at burnout. The APS report's discussion of the impact of drag (section 2.3.4 and figure 2.9) corrected the early arguments that missiles could deploy weapons and decoys too low for the defenses to reach. There is no significant disagreement—or impact on the defense.

Bloembergen and Patel: Wood and Canavan's long discussion of fast-burn boosters is now seen to be a non-issue for Canavan. The original version of APS report is correct as written.

Free-electron laser power and efficiency

A free-electron laser produces coherent radiation by sending an intense, energetic beam of electrons through an undulating magnetic field. Is the APS report correct when it says that a ground-based FEL would have to produce an average power of at least 1 gigawatt to be effective?

Canavan: Our *Analysis of the APS Report*² states (on page E2006) and *Concepts* derives (on page 19) that a 4-MW visible free-electron laser with a 4-meter mirror, or "4-4" platform, should have "performance roughly equivalent to a 20–10 chemical laser at 2.7 microns." For space basing, the cost and mass of the FEL platform are minimized by operation at the shortest wavelength compatible with visible optics, which the APS report indicates is in the visible (sections 5.2.2 and 5.2.3). *Concepts* used 0.5 microns (0.4 on page 18 is a typo), a wavelength at which FEL operation compatible with efficient scaling to 4 MW has been demonstrated. Power scales as wavelength, so that at 0.5 microns the power is reduced to about $(0.5/2.7) \times 20$ MW, or 3.7 MW. If a visible FEL were required to have the same power and mirror area as a 20–10 chemical laser, its brightness would be greater by a factor of $(2.7/0.5)^2$, or 29, and thus would be 7×10^{21} W/sr. A single laser of that brightness would be oversized to handle nominal engagements, by the APS report's own analysis. For meaningful comparisons brightness should be held constant, so the APS response's observation that a 4-MW FEL at 40% efficiency would require "only 10 MW of delivered power, rather than the 1 GW stated by the APS report," only reflects that the APS report's 1-GW power is unsupportable (*Concepts*, page 19).

Thermal kill requirements for free-electron lasers are similar to those for chemical lasers, so the APS report overestimates the power per FEL by a factor of $(20 \text{ MW})/(4 \text{ MW})$, or 5, and incorrectly assumes that a single FEL would engage all missiles, for a total error of a factor of 50. (Note added in proof: This point was debated in a House

Armed Services Committee hearing on 15 September 1987. At that hearing SDIO concurred with the position that there is no basis for APS's assumption that one laser would have to engage all missiles.) *Concepts* uses the 40% efficiency of recirculating FELs (APS report, chapter 3, references 79 and 80), but halving it would only increase the input power to $(4 \text{ MW})/0.2$, or 20 MW—a factor of 50 below the APS's 1 GW. The APS's ground-based FELs propagate better at wavelengths around 1 micron (APS report, section 5.4.1 and figure 5.15).

Bloembergen and Patel: The statements that Canavan quotes from reference 2 refer to space-based laser platform configurations. The 1-GW power mentioned in conclusion 3 in the executive summary of the APS report holds for thermal kill by one ground-based laser. The laser beam would be steered by a relay mirror in a geostationary orbit to a constellation of fighting mirrors, as discussed in chapter 5 of the APS report. Alternatively, one could consider architectures with several relay mirrors in high-altitude orbits lower than geostationary orbits. The much longer optical path required for ground-based laser systems invalidates Canavan's scaling arguments.

The architecture that Canavan alludes to on page 19 of his response² to the APS study involves many smaller ground-based FELs and is ill defined because the requirement for relay mirrors is completely ignored. Reference 2 puts the number of FELs at the number of fighting mirrors: 50–100. This may actually be more FELs than are necessary, because of the mirrors' absentee ratio—the ratio of space-based platforms over the launch area at the time of attack to the total number of platforms deployed in space. A number of relay mirrors at least equal to the number of lasers in action appears to be indispensable. But one must recall that five to seven lasers must be built for every one in the battle because of cloud cover restrictions. This and a number of other factors, such as dwell times, low retargeting rates and mirror filling errors, have led the Strategic Defense Initiative Organization's own systems architects to eliminate the option of many small ground-based lasers, and no detailed version was ever presented to the APS study group, for excellent reasons.

Returning to the architecture based on one ground-based free-electron laser, such a laser must indeed produce the same total power as the 50 ground-based lasers assumed by Canavan. In addition to the losses in atmospheric propagation, one must also allow for the fact that the long optical path and limitations on the size of the relay mirrors make it unlikely that one could achieve the small spot sizes on target that would follow from the scaling argument of reference 2. This adds another factor of at least 5 to the required ground-based power. Contrary to Canavan's claim, the power figure of 1 GW is correct for a ground-based FEL system of appropriate size and realistic efficiency using thermal kill mechanisms.³ The alleged error of a factor of 100 simply does not exist.

Neutral particle beam power

A beam of fast-moving atoms emitted by a space-based accelerator could penetrate deep into a missile or warhead, but how powerful would such a beam need to be?

Canavan: The APS response indicates that the 1-GW power estimated by the APS report for "beam particle accelerators" is actually for lasers, but power is only an issue for space-based FELs. The power of a properly scaled FEL is 4 MW, so at the APS report's 20% efficiency, the power required is $(4 \text{ MW})/0.2$, or 20 MW, 2% of the 1 GW assumed by the APS response. The 50-MW FEL posited in the APS response is too powerful by a factor of 12.5. If its mirrors were held at 10 m, its brightness would be too large by a factor of $12.5 \times (10/4)^2$, or 78. However, it is

unimportant that in this irrelevant configuration the power is 80 times too large; in a properly scaled platform, the power is 10–20 MW.

The APS response suggests that the correct neutral particle beam power is intermediate between that in the APS report and that in *Concepts*, but the APS report uses 100 J/g for “massive upset” (section 4.3), which actually corresponds to the energy for melting weapon components or detonating high explosives (section 6.4.2). Depositions of a few millijoules per gram can upset hardened circuits; neutral particle beam dose rates are high and have been difficult to harden against. According to SDIO a practical value for upset is about 1 J/g, and for the destruction of electronics, which is what the APS report presumably meant, the requirement is about 10 J/g.

The APS report deals with tradeoffs within a single platform, so its statement that “a few hundred MeV probably is a reasonable compromise” (section 4.3) is without basis; 100 MeV could be useful for early applications. Even the beam energy of 250 MeV given in the APS response only increases the beam power to 0.1 amp $\times$ 250 MeV, or 25 MW, and the input power to about 80 MW—over an order of magnitude below the 1 GW of the APS report and response. The APS response cites current losses in the stripping cell that neutralizes the beam, but on the time scale the APS group assumes (section 4.3.4), there is no fundamental reason for such losses. The ranges given in the APS response are inappropriate; where brightness is concerned, neutral particle beams scale much like other directed-energy weapons. *Concepts* (page 25) uses the APS report’s analysis to calculate that the electronics kill time is about 0.1 sec. The configuration in *Concepts* is not a “system minimum”; reasonable variations do not change *Concepts’* statement that there would be enough time to engage all missiles.⁸

Bloembergen and Patel: Canavan’s estimates are based on system parameters “useful for early applications.” The APS response clearly states the assumptions on which we derive a power requirement of 200 MW for space-based neutral particle beams. The range of powers would be from 100 MW to 1000 MW depending on the range and the retargeting rate. Conclusion 21 and the paragraph that follows it in the APS report were reworded for publication in *Reviews of Modern Physics* to avoid confusion.

Excimer laser energy and power

An electric discharge in a mixture of rare gas atoms and halogen molecules can cause the formation of electronically excited, ionically bound molecules such as krypton fluoride. When these so-called excimers make a radiative transition to unbound, ground state atoms, they emit at short wavelengths. Ground-based excimer lasers could emit intense pulses of radiation, but what energy and repetition rate must these pulses have to be of strategic military use?

Canavan: The APS report provides only one calculation of the “structural damage from impulse loading” at issue (section 6.3.5). This calculation was presented to the APS study group as a calculation of the impulse required for excimer lasers.⁹ The APS report states (section 6.3.1) that “coupling coefficients for short-wavelength lasers have recently been measured. . . . The parameters agree with theoretical calculations for one-dimensional spot sizes.” Experiments have therefore confirmed the excimer laser coupling and scaling used. The APS report uses the confirmed 5-kJ/cm² fluence coupling (equation 6.35) to predict a 10-cm spot radius for a one-dimensional interaction (equation 6.38), so the equations and parameters in the body of the APS report give a lethal energy of (5

kJ/cm²) π (10 cm)², or 1.57 MJ, which with the APS’s factor-of-4 transmission loss corresponds to 6 MJ, as *Concepts* states. However, the executive summary in the APS report states that “ground-based excimer lasers for strategic defense applications must produce at least 100 MJ of energy in single pulse.”

The APS report’s analysis prescribes 6 MJ per kill, so destroying 1000 missiles in 100 seconds, or 10 missiles/sec, with the 10 mirrors that would typically be in range would require a power of (6 MJ/kill) $\times$ (1 kill/sec), or 6 MW for each laser. Hence the total power would be 60 MW rather than the 1 GW given in conclusion 2 in the executive summary of the APS report, which assumes that a kill requires 100 MJ and that one laser must engage all targets. Pulsed lasers need not dwell; they need only hit the missile somewhere, so their control requirements are less stringent. APS responds by saying that “the SDIO has by its actions disagreed with Canavan’s assertion,” in that it has relegated excimer lasers “to being a ‘backup’ technology.” But all directed-energy weapons play a backup role to kinetic-energy weapons (*Concepts*, page 3). APS argues that the SDIO action justifies the APS report’s assessment, which appears to imply that further SDIO reductions on the basis of errors in the APS report would justify those errors. Physics determines what is right; budgets, only what is popular.

Bloembergen and Patel: Canavan quotes equation 6.38 of the APS report, which predicts a minimum spot size of 10 cm for a valid one-dimensional interaction. This implies that laboratory tests need at least this spot size. It is incorrect to equate this with the actual spot size on a target in space during a strategic defense engagement. A ground-based excimer laser system faces problems similar to those of a ground-based free-electron laser system: propagation through the atmosphere and long optical paths involving relay mirrors. In light of the problems, we estimate that achievable minimum spot sizes on target lie between 30 cm and 1 meter. This would require a minimum of about 25 MJ on target because the spot area is at least 10–20 times larger than Canavan assumes. As with a free-electron laser, each ground-based excimer laser requires one or more relay mirrors as well as the constellation of fighting mirrors. An architecture with an individual laser engaging all targets is justified. There are no errors of a factor of 160, as reference 2 alleges and Canavan reiterates.

Space-based power

Would orbiting strategic defense platforms require nuclear reactors to supply “housekeeping” power?

Canavan: Conclusion 20 in the executive summary of the APS report states that “housekeeping power [would] necessitate nuclear-reactor-driven power plants [producing] 100–700 kW of continuous power,” but the *Analysis of the APS Report*² states that the requirements could be met by “a few thousands to tens of thousands of watts for housekeeping—a requirement readily met by solar panels and storage batteries, without use of nuclear reactors” (page E2006). The APS response says instead that it estimated the power “to be in the 100-kW range . . . about a factor of two higher than the estimates presented to us by SDIO officials,” so there is no longer any disagreement. SDIO’s 50 kW is a few “tens of thousands of watts,” which could be satisfied without nuclear reactors.

Bloembergen and Patel: No detailed response is necessary except to say that a few tens of kilowatts of electrical power necessitates nuclear power reactors for two reasons. First is survivability: The large area needed for solar cells would make a satellite very vulnerable to actions of the offense. Second is reliability: The long expected stay in

orbit could reduce the availability of power because of the radiation damage that occurs over 10-year time scales, as discussed in the National Research Council report *Electric Power from Orbit: A Critique of a Satellite Power System* (National Academy Press, Washington, DC, 1981).

Closing statements

Canavan: The points in the APS response are not difficult to address individually, and taken together they demonstrate that while the APS report may have good physics, its analysis and scaling projections are sufficiently flawed that they should be redone or removed. Even in a tutorial one does not wish to use calculations that are off by factors of 2^n , if n ranges¹⁰ up to 20. The APS response had no argument with the discussion in *Concepts* (pages 37–55) of the role of directed-energy weapons in mid-course, which is probably more important than the boost phase. The ability of directed-energy weapons to interactively discriminate decoys from real weapons (*Concepts*, pages 37–50; APS report, sections 7.7–7.8) and intercept the latter (*Concepts*, pages 54–55) is pivotal. These issues could be usefully discussed at the level of this debate, as could survivability, which the APS report outlines (chapter 9) and *Concepts* bounds (pages 37–38). But they need a proper forum, which has been a problem (*Concepts*, pages 55–69). I thank APS and PHYSICS TODAY for providing one for this exchange.

Bloembergen and Patel: There is no disagreement on the basic physics and the equations to be used in discussing directed-energy weapons. All of this is made available to all physicists, scientists and engineers by publication of the APS report in *Reviews of Modern Physics*. Surprisingly, large disagreements can nevertheless arise, based on different assumptions about values of parameters in the equations. The most salient disagreement still existing relates to the minimum spot size that ground-based laser systems can achieve at the target. Here Canavan's analysis in reference 2 needs a much more thorough consideration of relay mirrors and atmospheric optics along lines similar to those used in chapter 5 of the APS report.

The official response of the Strategic Defense Initiative Organization to our report acknowledges our accurate description of the state-of-the-art directed-energy weapons technology at the time of the study's completion. SDIO's response goes on to say that the wording of many of our conclusions is "unduly pessimistic"; Canavan pushes estimates of achievable parameter values further toward more optimistic numbers. There are, undoubtedly, many other physicists, scientists and engineers, including some working actively on SDI-related projects, who believe instead that our conclusions are unduly optimistic. We believe our conclusions are realistic.

The APS study group, comprising 16 individuals with widely diverging political views, heard numerous presentations from many dedicated scientists working on SDI-related problems. They probably had an equally wide range of personal convictions. It is remarkable that a unanimous publication emerged from this effort. This was possible only because the group eliminated all politically motivated statements and narrowed the choice of scientific parameters to a reasonable range. We arrived at the final version of our report, published in *Reviews of Modern Physics*, only after careful consideration of the criticisms in reference 2. We reject Canavan's statement that the "analysis and scaling projections [in the APS report] are sufficiently flawed that they should be redone or removed."

We reject in stronger terms the additional, gratuitous statement, "Even in a tutorial one does not wish to use cal-

culations that are off by factors of 2^n , if n ranges up to 20." Here Canavan endorses and lends scientific credibility to a letter that appeared in *The Wall Street Journal*.¹⁰ We had until now declined public comment on this letter, as it is political rather than scientific in character. However, an allegation in PHYSICS TODAY of an error of 2^{20} cannot be ignored.

The starting point for the *Journal* letter was the statement in section 5.2.1 of the original version of the APS report that the total system cost of the 2.4-meter primary mirror for the Hubble Space Telescope is about 1.2 billion 1984 dollars. In this statement we made reference to an article in *Science*.¹¹ It should be clear from this reference that the cost refers to the entire system, and this was stated explicitly in the APS report. Russell Seitz, the author of the *Journal* letter quoted by Canavan, chose to read this as the mirror cost even after explicit discussions with us in which we pointed out the phrase "system cost." The fabrication cost of the 2.4-meter mirror alone is \$5 million. To avoid misunderstanding, the *Reviews of Modern Physics* version of the APS report spells out explicitly both the mirror cost and the system cost, and Seitz was informed of this before publication of his cost estimates in *The Wall Street Journal*. The APS study made no cost estimates whatsoever. Canavan's allegation that our report contains an error of 2^n has no basis in fact.

Canavan's ten points do not necessitate any changes in the APS report as published in *Reviews of Modern Physics*. As noted above, the RMP version differs from the April 1987 report only in the correction of a clerical error regarding chemical laser power and minor rewording in a few places to avoid ambiguity or misinterpretation.

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