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# Space-based Ballistic-Missile Defense

*President Reagan's "Star Wars" program seems unlikely ever to protect the entire nation against a nuclear attack. It would nonetheless trigger a major expansion of the arms race*

by Hans A. Bethe, Richard L. Garwin, Kurt Gottfried and Henry W. Kendall

For two decades both the U.S. and the U.S.S.R. have been vulnerable to a devastating nuclear attack, inflicted by one side on the other in the form of either a first strike or a retaliatory second strike. This situation did not come about as the result of careful military planning. "Mutual assured destruction" is not a policy or a doctrine but rather a fact of life. It simply descended like a medieval plague—a seemingly inevitable consequence of the enormous destructive power of nuclear weapons, of rockets that could hurl them across almost half of the globe in 30 minutes and of the impotence of political institutions in the face of such momentous technological innovations.

This grim development holds different lessons for different people. Virtually everyone agrees that the world must eventually escape from the shadow of mutual assured destruction, since few are confident that deterrence by threat of retaliation can avert a holocaust indefinitely. Beyond this point, however, the consensus dissolves. Powerful groups in the governments of both superpowers apparently believe that unremitting competition, albeit short of war, is the only realistic future one can plan for. In the face of much evidence to the contrary they act as if the aggressive exploitation for military purposes of anything technology has to offer is critical to the security of the nation they serve. Others seek partial measures that could at least curb the arms race, arguing that this approach has usually been sidetracked by short-term (and shortsighted) military and political goals. Still others have placed varying degrees of faith in radical solutions: novel political moves, revolutionary technological advances or some combination of the two.

President Reagan's Strategic Defense Initiative belongs in this last category. In his televised speech last year calling on the nation's scientific community "to give us the means of rendering these nuclear weapons impotent and obsolete" the president expressed the hope that a technological revolution would enable the U.S. to "intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies." If such a breakthrough could be achieved, he said, "free people could live secure in the knowledge that their security did not rest upon the threat of instant U.S. retaliation."

Can this vision of the future ever become reality? Can any system for ballistic-missile defense eliminate the threat of nuclear annihilation? Would the quest for such a defense put an end to the strategic-arms race, as the president and his supporters have suggested, or is it more likely to accelerate that race? Does the president's program hold the promise of a secure and peaceful world or is it perhaps the most grandiose manifestation of the illusion that science can re-create the world that disappeared when the first nuclear bomb was exploded in 1945?

These are complex questions, with intertwined technical and political strands. They must be examined carefully before the U.S. commits itself to the quest for such a defense, because if the president's dream is to be pursued, space will become a potential field of confrontation and battle. It is partly for this reason the Strategic Defense Initiative is commonly known as the "Star Wars" program.

This article, which is based on a forthcoming book by a group of us associated with the Union for Concerned Scientists, focuses on the technical aspects of the issue of space-based ballistic-missile defense. Our discussion of the political implications of the president's Strategic Defense Initiative will draw on the work of two of our colleagues, Peter A. Clausen of the Union for Concerned Scientists and Richard Ned Lebow of Cornell University.

The search for a defense against nuclear-armed ballistic missiles began three decades ago. In the 1960's both superpowers developed anti-ballistic-missile (ABM) systems based on the use of interceptor missiles armed with nuclear warheads. In 1968 the U.S.S.R. began to operate an ABM system around Moscow based on the Galosh interceptor, and in 1974 the U.S. completed a similar system to protect Minuteman missiles near Grand Forks Air Force Base in North Dakota. (The U.S. system was dismantled in 1975.)

Although these early efforts did not provide an effective defense against a major nuclear attack, they did stimulate two developments that have been dominant features of the strategic landscape ever since: the ABM Treaty of 1972 and the subsequent deployment of multiple independently targetable reentry vehicles (MIRV's), first by the U.S. and later by the U.S.S.R.

In the late 1960's a number of scientists who had been involved in investi-

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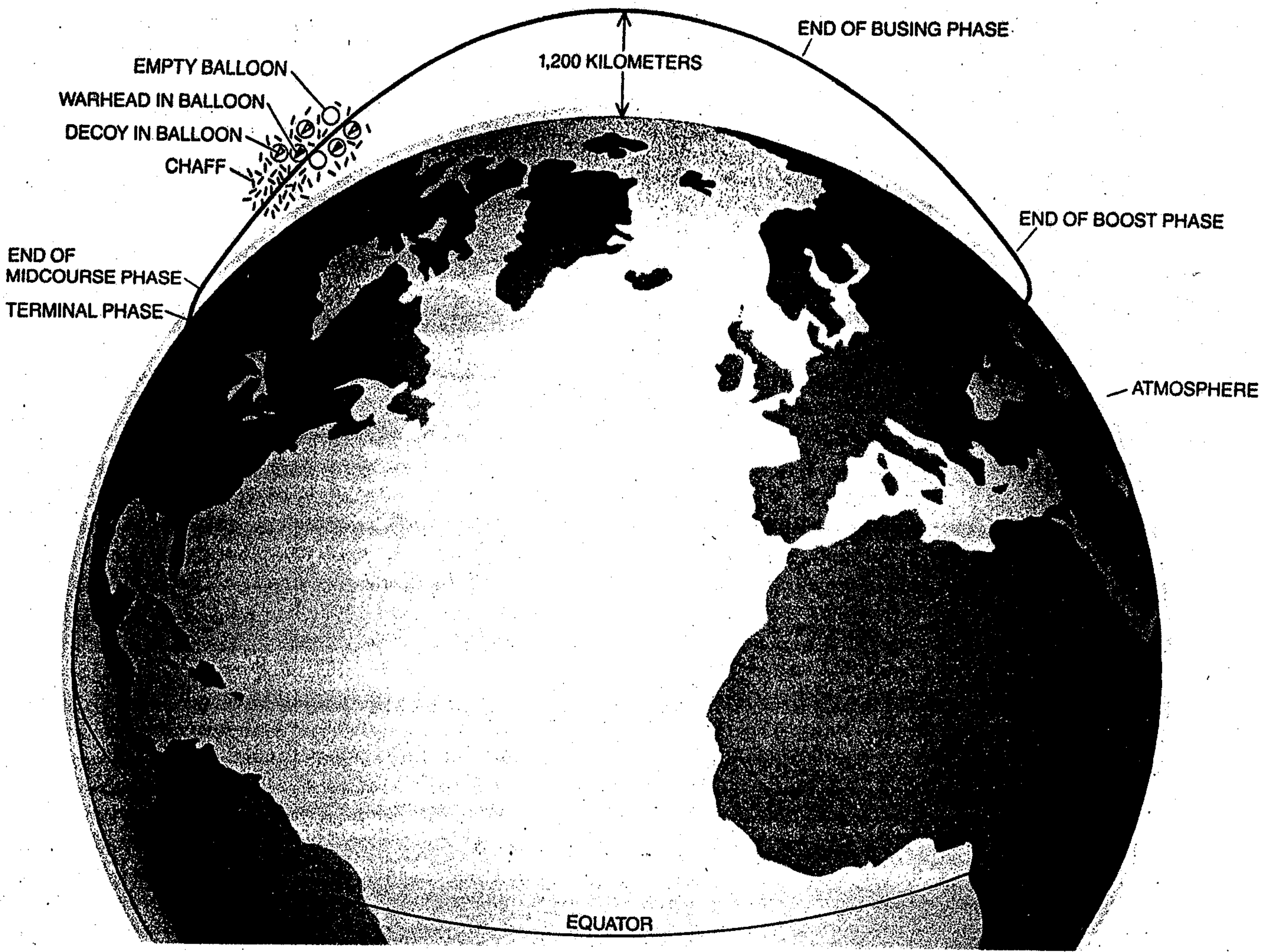


**FOUR DISTINCT PHASES** are evident in the flight of an intercontinental ballistic missile (ICBM). In boost phase the missile is carried above the atmosphere by a multistage booster rocket. Most modern strategic missiles carry multiple independently targetable reentry vehicles (MIRV's), which are released sequentially by a maneuverable "bus" during the busing, or postboost, phase. If the country under attack had a ballistic-missile-defense system, the bus would also dispense a variety of "penetration aids," such as decoys, balloons enclosing MIRV's and decoys, empty balloons, radar-reflecting wires called chaff and infrared-emitting aerosols. During the midcourse phase the heavy MIRV's and the light penetration aids would follow essentially identical trajectories. In the terminal phase this "threat cloud" would reenter the atmosphere, and friction with the air would retard the penetration aids much more than the MIRV's. For ICBM's the flight would last between 25 and 30 minutes; for submarine-launched ballistic missiles (SLBM's) it could be as short as eight to 10 minutes.

| MISSILE | GROSS WEIGHT (KILOGRAMS) | END OF BOOST PHASE |  | END OF BUSING |  | USUAL PAYLOAD |
|---|---|---|---|---|---|---|
|  |  | TIME (SECONDS) | ALTITUDE (KILOMETERS) | TIME (SECONDS) | ALTITUDE (KILOMETERS) |  |
| SS-18 | 220,000 | 300 | 400 | ? | ? | 10 MIRV'S ON ONE BUS |
| MX | 89,000 | 180 | 200 | 650 | 1,100 | 10 MIRV'S ON ONE BUS |
| MX WITH FAST-BURNING BOOSTER | 87,000 | 50 | 90 | 60 | 110 | SEVERAL MICROBUSES WITH MIRV'S AND PENETRATION AIDS |
| MIDGETMAN | 19,000 | 220 | 340 | — | — | SINGLE WARHEAD |
| MIDGETMAN WITH FAST-BURNING BOOSTER | 22,000 | 50 | 80 | — | — | SINGLE WARHEAD WITH PENETRATION AIDS |

**CHARACTERISTICS OF FIRST TWO PHASES** in the flight of an ICBM are given for five missiles: the SS-18, a very large, multiple-warhead ICBM already deployed by the U.S.S.R.; the MX, a large, multiple-warhead ICBM currently under development by the U.S.; the Midgetman, a smaller, single-warhead ICBM now in the early planning stages in the U.S., and two hypothetical missiles comparable to the MX and the Midgetman that have been specifically designed to counter a boost-phase ballistic-missile-defense system. In this case the assumption is that both missiles would be equipped not only with suitable penetration aids but also with fast-burning boosters, thereby reducing the time available for the defense to detect their infrared emission. The SS-18 is constrained under the terms of the SALT II Treaty to carry no more than 10 MIRV's; it is actually capable of carrying 30 or more smaller warheads. A single-warhead missile such as Midgetman need have no bus and hence there would be no distinction in its case between the postboost phase and the midcourse phase. The table is adapted from a report prepared by Ashton B. Carter for the Congressional Office of Technology Assessment.

gating the possibility of ballistic-missile defense in their capacity as high-level advisers to the U.S. Government took the unusual step of airing their criticism of the proposed ABM systems both in congressional testimony and in the press [see "Anti-Ballistic-Missile Systems," by Richard L. Garwin and Hans A. Bethe; SCIENTIFIC AMERICAN, March, 1968]. Many scientists participated in the ensuing debate, and eventually a consensus emerged in the scientific community regarding the flaws in the proposed systems.

The scientists' case rested on a technical assessment and a strategic prognosis. On the technical side they pointed out that the systems then under consideration were inherently vulnerable to deception by various countermeasures and to preemptive attack on their exposed components, particularly their radars. On the strategic side the scientists argued that the U.S.S.R. could add enough missiles to its attacking force to ensure penetration of any such defense. These arguments eventually carried the day, and they are still germane. They were the basis for the ABM Treaty, which was signed by President Nixon and General Secretary Brezhnev in Moscow in May, 1972. The ABM Treaty formally recognized that not only the deployment but also the development of such defensive systems would have to be strictly controlled if the race in offensive missiles was to be contained.

MIRV's were originally conceived as the ideal countermeasure to ballistic-missile defense, and in a logical world they would have been abandoned with the signing of the ABM Treaty. Nevertheless, the U.S. did not try to negotiate a ban on MIRV's. Instead it led the way to their deployment in spite of repeated warnings by scientific advisers and the Arms Control and Disarmament Agency to senior Government officials that MIRV's would undermine the strategic balance and ultimately be to the advantage of the U.S.S.R. because of its larger ICBM's. The massive increase in the number of nuclear warheads in both strategic arsenals during the 1970's is largely attributable to the introduction of MIRV's. The result, almost everyone now agrees, is a more precarious strategic balance.

The president's Strategic Defense Initiative is much more ambitious than the ABM proposals of the 1960's. To protect an entire society a nationwide defense of "soft" targets such as cities would be necessary; in contrast, the last previous U.S. ABM plan—the Safeguard system proposed by the Nixon Administration in 1969—was intended to provide only a "point" defense of "hard" targets such as missile silos and command bunkers. The latter mission could be accomplished by a quite permeable terminal-defense system that intercepted warheads very close to their targets, since a formidable retaliatory capability would remain even if most of the missile silos were destroyed. A large metropolitan area, on the other hand, could be devastated by a handful of weapons detonated at high altitude; if necessary, the warheads could be designed to explode on interception.

To be useful a nationwide defense would have to intercept and eliminate virtually all the 10,000 or so nuclear warheads that each side is currently capable of committing to a major strategic attack. For a city attack it could not wait until the atmosphere allowed the defense to discriminate between warheads and decoys. Such a high rate of attrition would be conceivable only if there were several layers of defense, each of which could reliably intercept a large percentage of the attacking force. In particular, the first defensive layer would have to destroy most of the attacking warheads soon after they left their silos or submerged submarines, while the booster rockets were still firing. Accordingly boost-phase interception would be an indispensable part of any defense of the nation as a whole.

Booster rockets rising through the atmosphere thousands of miles from U.S. territory could be attacked only from space. That is why the Strategic Defense Initiative is regarded primarily as a space-weapons program. If the president's plan is actually pursued, it will mark a turning point in the arms race perhaps as significant as the introduction of ICBM's.

Several quite different outcomes of the introduction of space weapons have been envisioned. One view (apparently widely held in the Reagan Administration) has been expressed most succinctly by Robert S. Cooper, director of the Defense Advanced Research Projects Agency. Testifying last year before the Armed Services Committee of the House of Representatives, Cooper declared: "The policy for the first time recognizes the need to control space as a military environment." Indeed, given the intrinsic vulnerability of space-based systems, the domination of space by the U.S. would be a prerequisite to a reliable ballistic-missile defense of the entire nation. For that reason, among others, the current policy also calls for the acquisition by the U.S. of antisatellite weapons [see "Antisatellite Weapons," by Richard L. Garwin, Kurt Gottfried and Donald L. Hafner; SCIENTIFIC AMERICAN, June].

The notion that the U.S. could establish and maintain supremacy in space ignores a key lesson of the post-Hiroshima era: a technological breakthrough of even the most dramatic and unexpected nature can provide only a temporary advantage. Indeed, the only outcome one can reasonably expect is that both superpowers would eventually develop space-based ballistic-missile-defense systems. The effectiveness of these systems would be uncertain and would make the strategic balance more precarious than it is today. Both sides will have expanded their offensive forces to guarantee full confidence in their ability to penetrate defenses of unknown reliability, and the incentive to cut one's own losses by striking first in a crisis will be even greater than it is now. Whether or not weapons deployed in space could ever provide a reliable defense against ballistic missiles, they would be potent antisatellite weapons. As such they could be used to promptly destroy an opponent's early-warning and communications satellites, thereby creating a need for critical decisions at a tempo ill suited to the speed of human judgment.

Our analysis of the prospects for a space-based defensive system against ballistic-missile attack will focus on the problem of boost-phase interception. It is not only an indispensable part of the currently proposed systems but also what distinguishes the current concept from all previous ABM plans. On the basis of our technical analysis and our assessment of the most likely response of the U.S.S.R. we conclude that the pursuit of the president's program would inevitably stimulate a large increase in the Russian strategic offensive forces, further reduce the chances of controlling events in a crisis and possibly provoke the nuclear attack it was designed to prevent. In addition the reliability of the proposed defense would remain a mystery until the fateful moment at which it was attacked.

Before assessing the task of any defense one must first examine the likely nature of the attack. In this case we shall concentrate on the technical and military attributes of the land-based ICBM and on how a large number of such missiles could be used in combination to mount a major strategic attack.

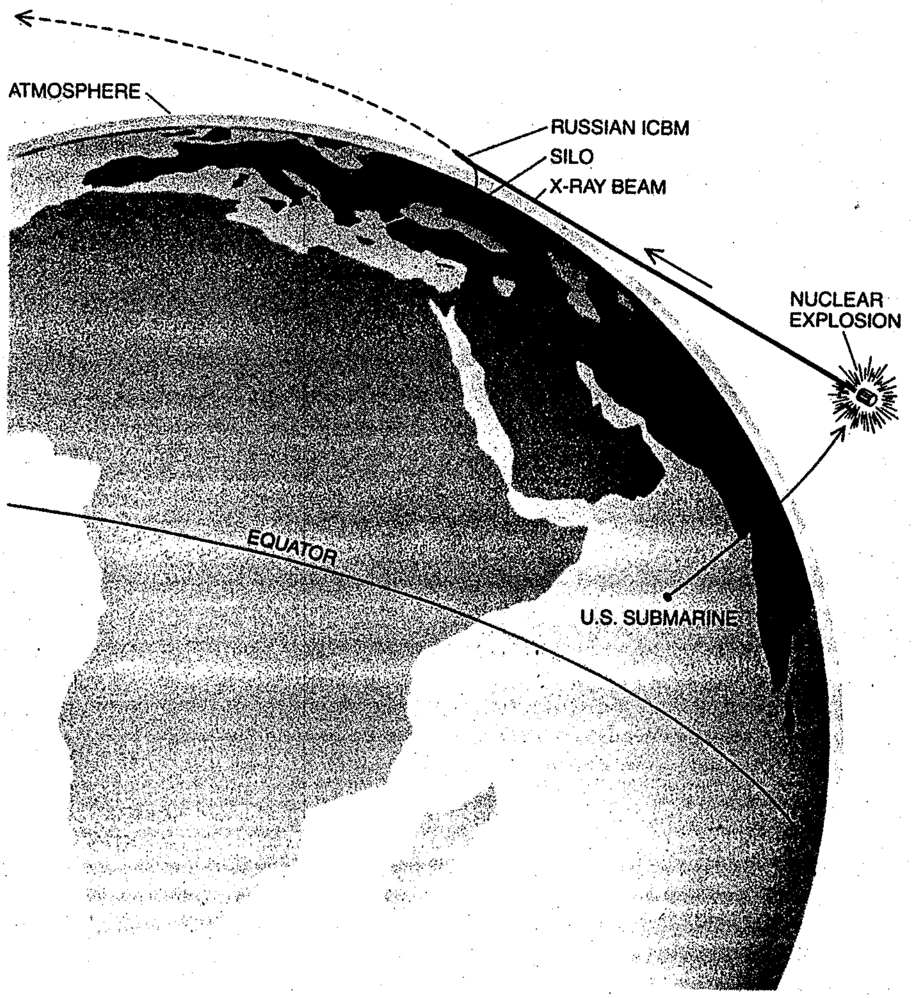
The flight of an ICBM begins when the silo door opens and hot gases eject the missile. The first-stage booster then ignites. After exhausting its fuel the first stage falls away as the second stage takes over; this sequence is usually repeated at least one more time. The journey from the launch point to where the main rockets stop burning is the boost phase. For the present generation of ICBM's the boost phase lasts for three to five minutes and ends at an altitude of 300 to 400 kilometers, above the atmosphere.

A typical ICBM in the strategic arsenal of the U.S. or the U.S.S.R. is equipped with MIRV's, which are dispensed by a maneuverable carrier vehicle called a bus after the boost phase ends. The bus releases the MIRV's one at a time along slightly different trajectories toward their separate targets. If there were defenses, the bus could also release a variety of penetration aids, such as lightweight decoys, reentry vehicles camouflaged to resemble decoys, radar-reflecting wires called chaff and infrared-emitting aerosols. Once the bus had completed its task the missile would be in midcourse. At that point the ICBM would have proliferated into a swarm of objects, each of which, no matter how light, would move along a ballistic trajectory indistinguishable from those of its accompanying objects. Only after the swarm reentered the atmosphere would the heavy, specially shaped reentry vehicles be exposed as friction with the air tore away the screen of lightweight decoys and chaff.

This brief account reveals why boost-phase interception would be crucial: every missile that survived boost phase would become a complex "threat cloud" by the time it reached midcourse. Other factors also amplify the importance of boost-phase interception. For one thing, the booster rocket is a much larger and more fragile target than the individual reentry vehicles are. For another, its flame is an abundant source of infrared radiation, enabling the defense to get an accurate fix on the missile. It is only during boost phase that a missile reveals itself by emitting an intense signal that can be detected at a large distance. In midcourse it must first be found by illuminating it with microwaves (or possibly laser light) and then sensing the reflected radiation, or by observing its weak infrared signal, which is due mostly to reflection of the earth's infrared radiation.

Because a nationwide defense must be capable of withstanding any kind of strategic attack, the exact nature of the existing offensive forces is immaterial to the evaluation of the defense. At present a full-scale attack by the U.S.S.R. on the U.S. could involve as many as 1,400 land-based ICBM's. The attack might well begin with submarine-launched ballistic missiles (SLBM's), since their unpredictable launch points and short flight times (10 minutes or less) would lend the attack an element of surprise that would be critical if the national leadership and the ground-based bomber force were high-priority targets.

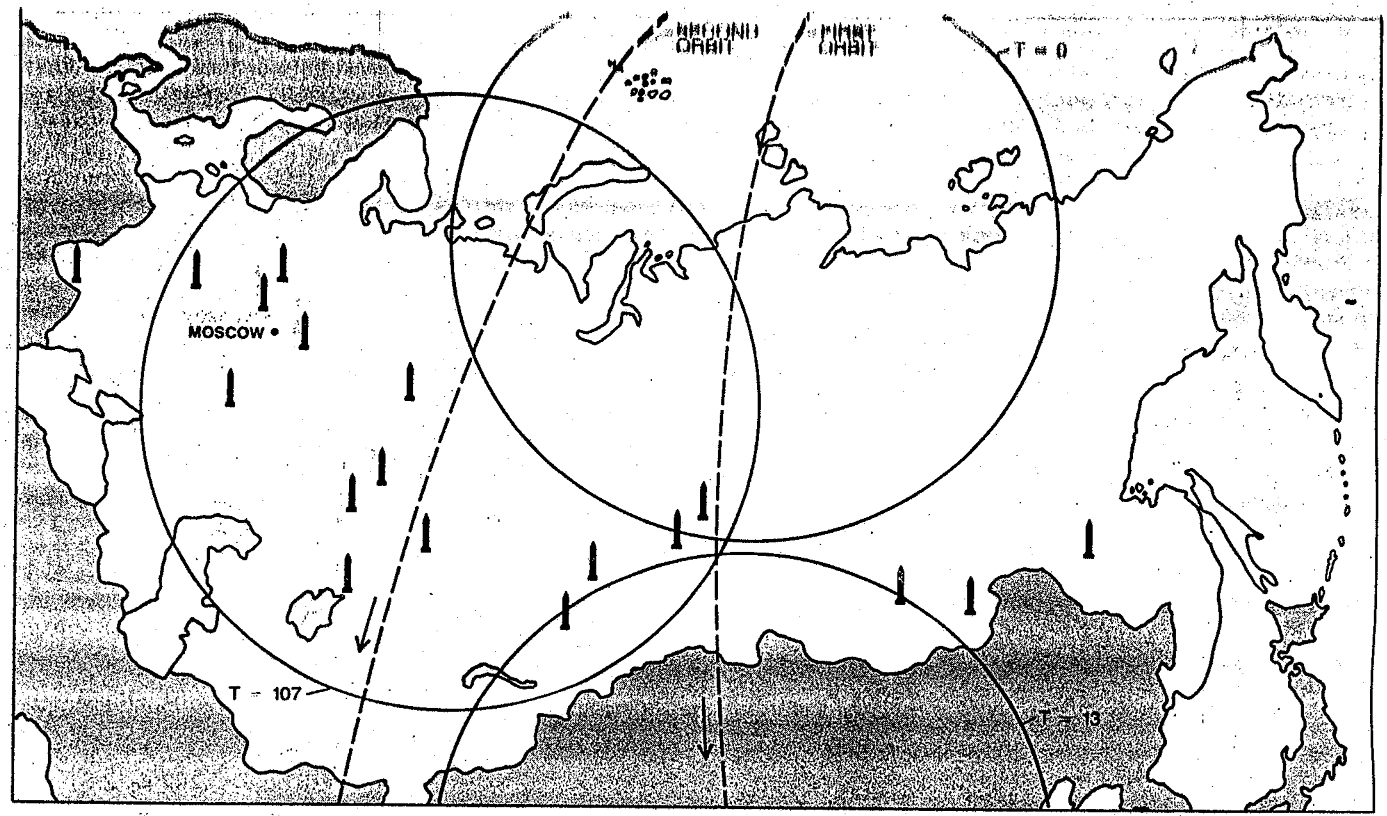
SLBM's would be harder to intercept than ICBM's, which spend 30 minutes or so on trajectories whose launch points are precisely known. Moreover, a space-based defense system would be unable to intercept ground-hugging cruise missiles, which can deliver nuclear warheads to distant targets with an accuracy that is independent of range. Both superpowers are developing sea-launched cruise missiles, and these weapons are certain to become a major part of their strategic forces once space-based ballistic-missile-defense systems appear on the horizon.



**"POP-UP" DEFENSIVE SYSTEM** would rely on a comparatively light interceptor launched from a submarine stationed in waters as close to the Russian ICBM fields as possible (in this case in the northern Indian Ocean). At present the leading candidate for this mission is the X-ray laser, a device consisting of a nuclear explosive surrounded by a cylindrical array of thin metallic fibers. Thermal X rays from the nuclear explosion would stimulate the emission of a highly directed beam of X-radiation from the fibers in the microsecond before the device was destroyed. In order to engage ICBM's similar to the MX rising out of the closest missile silos in the U.S.S.R. while they were still in their boost phase, the interceptor would have to travel at least 940 kilometers from the submarine to the point where the device would be detonated.

The boost-phase layer of the defense would require many components that are not weapons in themselves. They would provide early warning of an attack by sensing the boosters' exhaust plumes; ascertain the precise number of the attacking missiles and, if possible, their identities; determine the trajectories of the missiles and get a fix on them; assign, aim and fire the defensive weapons; assess whether or not interception was successful, and, if time allowed, fire additional rounds. This intricate sequence of operations would have to be automated, because the total duration of the boost phase, now a few minutes, is likely to be less than 100 seconds by the time the proposed defensive systems are ready for deployment.

If a sizable fraction of the missiles were to survive boost-phase interception, the midcourse defensive layer would have to deal with a threat cloud consisting of hundreds of thousands of objects. For example, each bus could dispense as many as 100 empty aluminized Mylar balloons weighing only 100 grams each. The bus would dispense reentry vehicles (and possibly some decoy reentry vehicles of moderate weight) enclosed in identical balloons. The balloons and the decoys would have the same optical and microwave "signature" as the camouflaged warheads, and therefore the defensive system's sensors would not be able to distinguish between them. The defense would have to disturb the threat cloud in some way in order to find the heavy reentry vehicles, perhaps by detonating a nuclear explosive in the path of the cloud. To counteract such a measure, however, the reentry vehicles could be designed to release more balloons. Alternatively, the midcourse defense could be designed to tar-



COVERAGE OF THE U.S.S.R. by an antimissile weapon with a range of 3,000 kilometers deployed in a polar orbit at an altitude of 1,000 kilometers is indicated by the three circles on this map. The circles show the extent of the weapon's effect at two times separated by 13 minutes on one circuit of the earth and at another time 94 minutes later, on the next circuit. The orbiting weapon could be either a laser or a "fighting mirror" designed to reflect the light sent to it by a mirror stationed at an altitude of 36,000 kilometers above the Equator.

get everything in the threat cloud, a prodigious task that might be beyond the supercomputers expected a decade from now. In short, the midcourse defense would be overwhelmed unless the attacking force was drastically thinned out in the boost phase.

Because the boosters would have to be attacked while they could not yet be seen from any point on the earth's surface accessible to the defense, the defensive system would have to initiate boost-phase interception from a point in space, at a range measured in thousands of kilometers. Two types of "directed energy" weapon are currently under investigation for this purpose: one type based on the use of laser beams, which travel at the speed of light (300,000 kilometers per second), and the other based on the use of particle beams, which are almost as fast. Nonexplosive projectiles that home on the booster's infrared signal have also been proposed.

There are two alternatives for basing such weapons in space. They could be in orbit all the time or they could be "popped up" at the time of the attack. There are complementary advantages and disadvantages to each approach. With enough weapons in orbit some would be "on station" whenever they were needed, and they could provide global coverage; on the other hand, they would be inefficient because of the number of weapons that would have to be actively deployed, and they would be extremely vulnerable. Pop-up weapons would be more efficient and less vulnerable, but they would suffer from formidable time constraints and would offer poor protection against a widely dispersed fleet of strategic submarines.

Pop-up interceptors of ICBM's would have to be launched from submarines, since the only accessible points close enough to the Russian ICBM silos are in the Arabian Sea and the Norwegian Sea, at a distance of more than 4,000 kilometers. An interceptor of this type would have to travel at least 940 kilometers before it could "see" an ICBM just burning out at an altitude of 200 kilometers. If the interceptor were lofted by an ideal instant-burn booster with a total weight-to-payload ratio of 14 to one, it could reach the target-sighting point in about 120 seconds. For comparison, the boost phase of the new U.S. MX missile (which has a weight-to-payload ratio of 25 to one) is between 150 and 180 seconds. In principle, therefore, it should just barely be possible by this method to intercept a Russian missile comparable to the MX, provided the interception technique employed a beam that moves at the speed of light. On the other hand, it would be impossible to intercept a large number of missiles, since many silos would be more than 4,000 kilometers away, submarines cannot launch all their missiles simultaneously and 30 seconds would leave virtually no time for the complex sequence of operations the battle-management system would have to perform.

A report prepared for the Fletcher panel, the study team set up last year by the Department of Defense under the chairmanship of James C. Fletcher of the University of Pittsburgh to evaluate the Strategic Defense Initiative for the president, bears on this question. According to the report, it is possible to build ICBM's that could complete the boost phase and disperse their MIRV's in only 60 seconds, at a sacrifice of no more than 20 percent of payload. Even with zero decision time a hypothetical instant-burn rocket that could pop up an interceptor system in time for a speed-of-light attack on such an ICBM would need an impossible weight-to-payload ratio in excess of 800 to one! Accordingly all pop-up interception schemes, no matter what kind of antimissile weapon they employ, depend on the assumption that the U.S.S.R. will not build ICBM's with a boost phase so short that no pop-up system could view the burning booster.

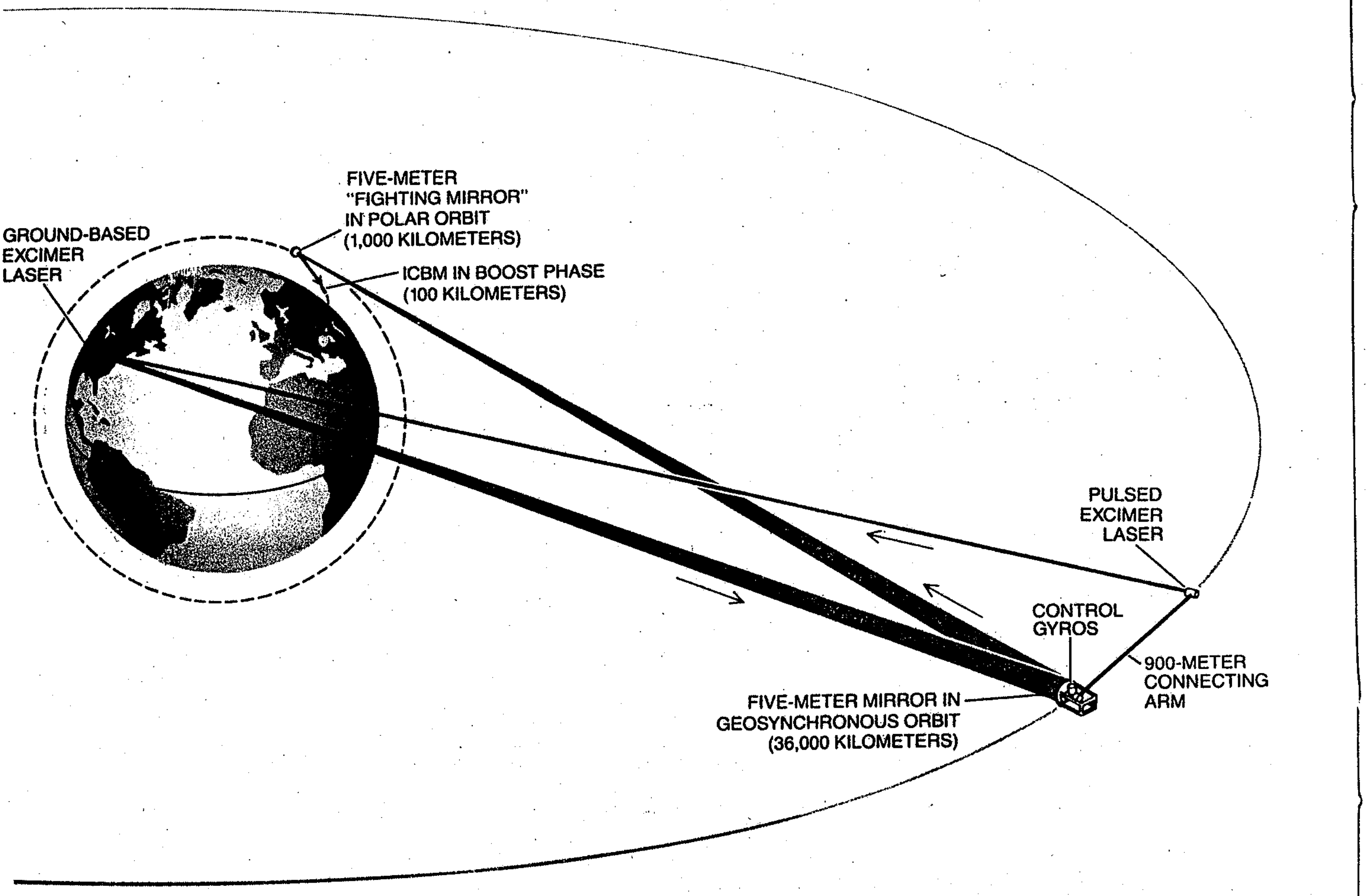
The time constraint faced by pop-up schemes could be avoided by putting at least some parts of the system into orbit. An antimissile satellite in a low orbit would have the advantage of having the weapon close to its targets, but it would suffer from the "absentee" handicap: because of its own orbital motion, combined with the earth's rotation, the ground track of such a satellite would pass close to a fixed point on the earth's surface only twice a day. Hence for every low-orbit weapon that was within range of the ICBM silos many others would be "absentees": they would be below the horizon and unable to take part in the defense. This unavoidable replication would depend on the range of the defensive weapon, the altitude and inclination of its orbit and the distribution of the enemy silos.

The absentee problem could be solved by mounting at least some components of the defensive system on a geosynchronous satellite, which remains at an altitude of some 36,000 kilometers above a fixed point on the Equator, or approximately 39,000 kilometers from the Russian ICBM fields. Whichever weapon were used, however, this enormous range would make it virtually impossible to exploit the radiation from the booster's flame to accurately fix an aim point on the target. The resolution of any optical instrument, whether it is an observing telescope or a beam-focusing mirror, is limited by the phenomenon of diffraction. The smallest spot on which a mirror can focus a beam has a diameter that depends on the wavelength of the radiation, the aperture of the instrument and the distance to the spot. For infrared radiation from the booster's flame the wavelength would typically be one micrometer, so that targeting on a spot 50 centimeters across at a range of 39,000 kilometers would require a precisely shaped mirror 100 meters across—roughly the length of a football field. (For comparison, the largest telescope mirrors in the world today are on the order of five meters in diameter.)

The feasibility of orbiting a high-quality optical instrument of this stupendous size seems remote. The wavelengths used must be shortened, or the viewing must be reduced, or both. Accordingly it has been suggested that a geosynchronous defensive system might be augmented by other optical elements deployed in low orbits.

One such scheme that has been proposed calls for an array of ground-based excimer lasers designed to work in conjunction with orbiting optical elements. The excimer laser incorporates a pulsed electron beam to excite a mixture of gases such as xenon and chlorine into a metastable molecular state, which spontaneously reverts to the molecular ground state; the latter in turn immediately dissociates into two atoms, emitting the excess energy in the form of ultraviolet radiation at a wavelength of .3 micrometer.

Each ground-based excimer laser would send its beam to a geosynchronous mirror with a diameter of five meters, and the geosynchronous mirror would in turn reflect the beam toward an appropriate "fighting mirror" in low orbit. The fighting mirror would then redi-



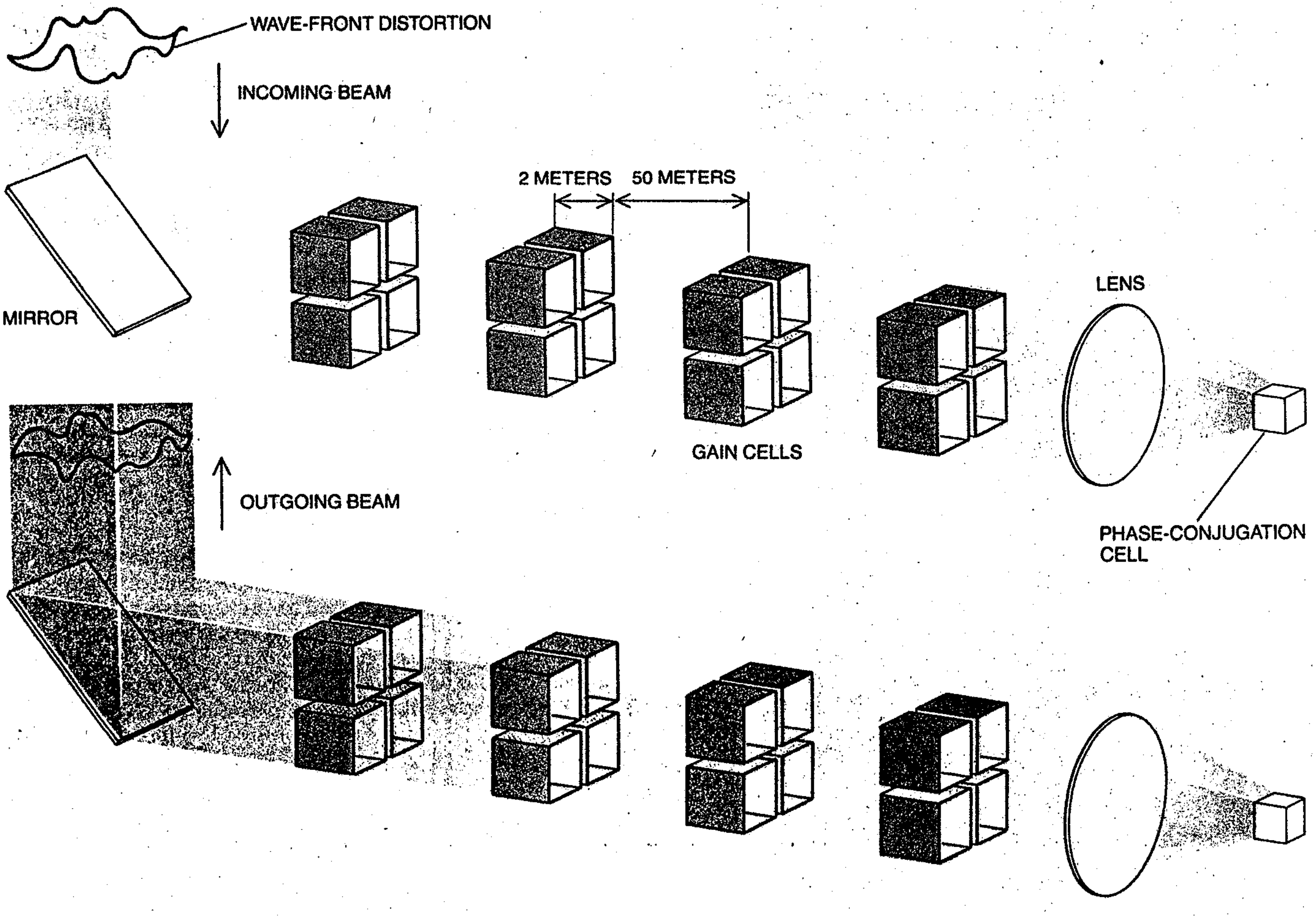
**GROUND-BASED LASER WEAPON** with orbiting optical elements is designed to intercept ICBM's in boost phase. The excimer laser produces an intense beam of ultraviolet radiation at a wavelength of .3 micrometer. The ground-based mirror would send its beam to a five-meter geosynchronous mirror, which would in turn reflect the beam toward a similar fighting and viewing mirror in a comparatively low orbit; this mirror would then reflect the beam toward the rising booster, depending on its ability to form an image of the infrared radiation from the booster's exhaust plume to get a fix on the target (*diagram at left*). In order to compensate for fluctuations in the density rect and concentrate the beam onto the rising booster rockets, depending on an accompanying infrared telescope to get an accurate fix on the boosters.

The main advantage of this scheme is that the intricate and heavy lasers, together with their substantial power supplies, would be on the ground rather than in orbit. The beam of any ground-based laser, however, would be greatly disturbed in an unpredictable way by ever present fluctuations in the density of the atmosphere, causing the beam to diverge and lose its effectiveness as a weapon. One of us (Garwin) has described a technique to compensate for these disturbances, making it possible, at least in principle, to intercept boosters by this scheme [*see illustration on these two pages*].

Assuming that such a system could be made to work perfectly, its power requirement can be estimated. Such an exercise is illuminating because it gives an impression of the staggering total cost of the system. Again information from the Fletcher panel provides the basis for our estimate. Apparently the "skin" of a booster can be "hardened" to withstand an energy deposition of 200 megajoules per square meter, which is roughly what is required to evaporate a layer of carbon three millimeters thick. With the aid of a geosynchronous mirror five meters in diameter and a fighting and viewing mirror of the same size, the beam of the excimer laser described above would easily be able to make a spot one meter across on the skin of a booster at a range of 3,000 kilometers from the fighting mirror; the resulting lethal dose would be about 160 megajoules.

A successful defense against an attack by the 1,400 ICBM's in the current Russian force would require a total energy deposition of 225,000 megajoules. (A factor of about 10 is necessary to compensate for atmospheric absorption, reflection losses at the mirrors and overcast skies.) If the time available for interception were 100 seconds and the lasers had an electrical efficiency of 6 percent, the power requirement would be more than the output of 300 1,000-megawatt power plants, or more than 60 percent of the current electrical generating capacity of the entire U.S. Moreover, this energy could not be extracted instantaneously from the national power grid, and it could not be stored by any known technology for instantaneous discharge. Special power plants would have to be built; even though they would need to operate only for minutes, an investment of $300 per kilowatt is a reasonable estimate, and so the outlay for the power supply alone would exceed $100 billion.

This partial cost estimate is highly optimistic. It assumes that all the boosters could be destroyed on the first shot, that the Russians would not have shortened the boost phase of their ICBM's, enlarged their total strategic-missile force or installed enough countermeasures to degrade the defense significantly by the time this particular defensive system was ready for deployment at the end of the century. Of course the cost of the entire system of lasers, mirrors, sensors



**of the atmosphere the geosynchronous satellite would be equipped with a smaller excimer laser mounted on a 900-meter connecting arm ahead of the main mirror. A pulse of ultraviolet radiation from this laser would be directed at the ground-based laser, which would reverse the phase of the incoming beam and would emit a much more intense outgoing beam that would exactly precompensate for the atmospheric disturbance encountered by the incoming beam (*diagram at right*). The gain cells would be powered by pulsed electron beams synchronized with the outgoing beam. Such difficulties as mirror vulnerability must be resolved if such a device is ever to be effective.**

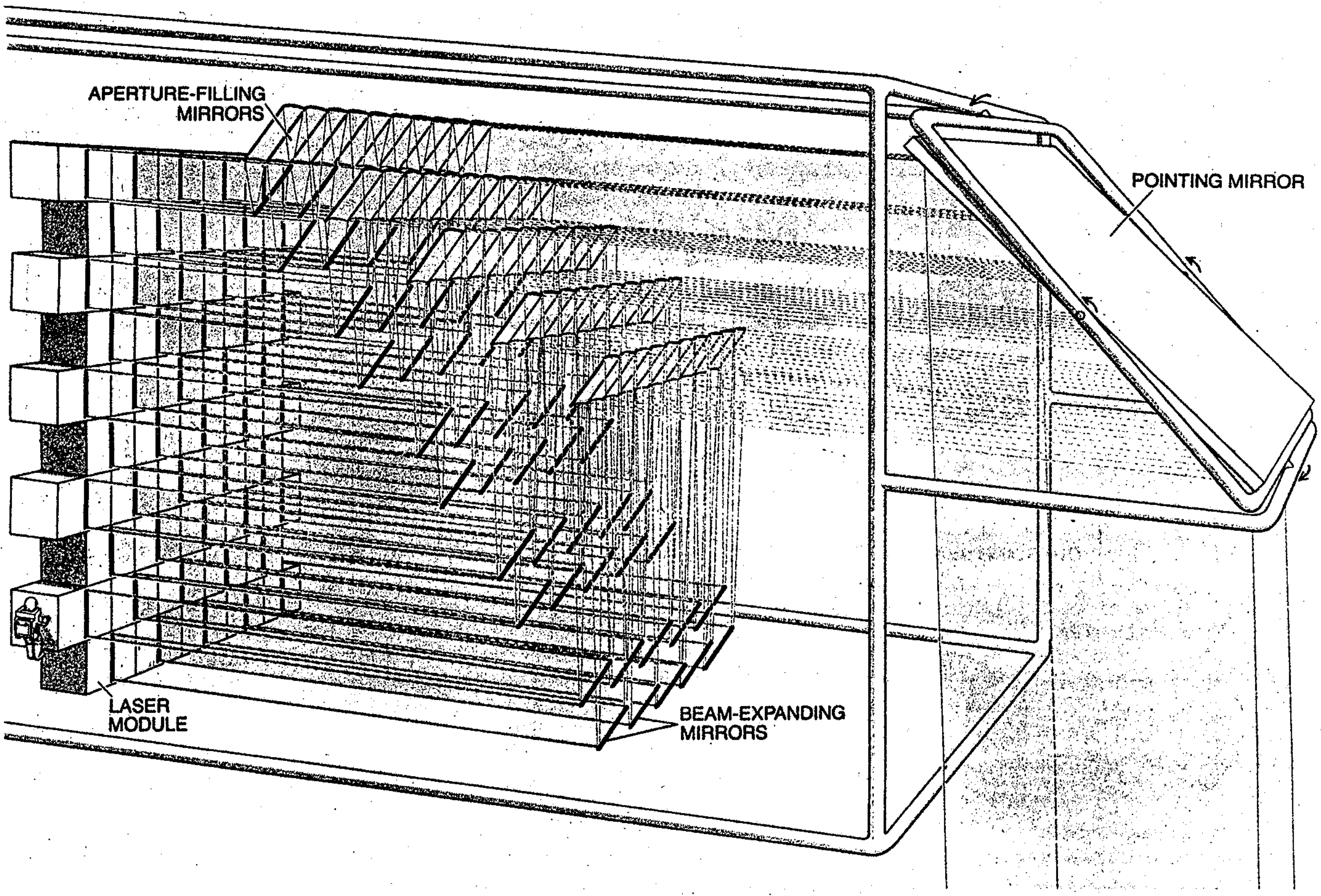
and computers would far exceed the cost of the power plant, but at this stage virtually all the required technologies are too immature to allow a fair estimate of their cost.

The exact number of mirrors in the excimer scheme depends on the intensity of the laser beams. For example, if the lasers could deliver a lethal dose of heat in just five seconds, one low-orbit fighting mirror could destroy 20 boosters in the assumed time of 100 seconds. It follows that 70 mirrors would have to be within range of the Russian silos to handle the entire attack, and each mirror would need to have a corresponding mirror in a geosynchronous orbit. If the distance at which a fighting mirror could focus a small enough spot of light was on the order of 3,000 kilometers, there would have to be about six mirrors in orbit elsewhere for every one "on station" at the time of the attack, for a total of about 400 fighting mirrors. This allowance for absenteeism is also optimistic, in that it assumes the time needed for targeting would be negligible, there would be no misses, the Russian countermeasures would be ineffective and excimer lasers far beyond the present state of the art could be built.

The second boost-phase interception scheme we shall consider is a pop-up system based on the X-ray laser, the only known device light enough to be a candidate for this role. As explained above, shortening the boost phase of the attacking missiles would negate any pop-up scheme. In this case a shortened boost phase would be doubly crippling, since the booster would stop burning within the atmosphere, where X rays cannot penetrate. Nevertheless, the X-ray laser has generated a good deal of interest, and we shall consider it here even though it would be feasible only if the Russians were to refrain from adapting their ICBM's to thwart this threat.

The X-ray laser consists of a cylindrical array of thin fibers surrounding a nuclear explosive. The thermal X rays generated by the nuclear explosion stimulate the emission of X-radiation from the atoms in the fibers. The light produced by an ordinary optical laser can be highly collimated, or directed, because it is reflected back and forth many times between the mirrors at the ends of the laser. An intense X-ray beam, however, cannot be reflected in this way, and so the proposed X-ray laser would emit a rather divergent beam; for example, at a distance of 4,000 kilometers it would make a spot about 200 meters across.

The U.S. research program on X-ray lasers is highly classified. According to a Russian technical publication, however, such a device can be expected to operate at an energy of about 1,000 electron volts. Such a "soft" X-ray pulse would be absorbed in the outermost fraction of a micrometer of a booster's skin, "blowing off" a thin surface layer. This would have two effects. First, the booster as a whole would recoil. The inertial-guidance system would presumably sense the blow, however, and it could still di-



**ORBITING LASER WEAPON** is shown in this highly schematic diagram based on several assumptions about the physical requirements of such a system. The weapon, which is designed to intercept ICBM's in boost phase from a comparatively low earth orbit, is scaled to generate a total of 25 megawatts of laser light at a wavelength of 2.7 micrometers from a bank of 50 chemical lasers, utilizing hydrogen fluoride as the lasing medium. The lasers, each of which occupies a cubic volume approximately two meters on a side, are arranged to produce an output beam with a square cross section 10 meters on a side. Assuming that the light from the entire bank of laser modules is in phase and that all the mirrors are optically perfect, it can be calculated that a weapon of this type could deliver a lethal dose of heat in seven seconds to a booster at a "kill radius" of some 3,000 kilometers. Some 300 such lasers would be needed in orbit to destroy the 1,400 ICBM's in the current Russian arsenal, assuming no countermeasures were taken other than "hardening" the missiles. Only the front of the weapon is shown; the fuel supply and other components would presumably be mounted behind the laser modules, to the left.

rect the warheads to their targets. Second, the skin would be subjected to an abrupt pressure wave that, in a careless design, could cause the skin to shear at its supports and damage the booster's interior. A crushable layer installed under the skin could prolong and weaken the pressure wave, however, thereby protecting both the skin and its contents.

Other interception schemes proposed for ballistic-missile defense include chemical-laser weapons, neutral-particle-beam weapons and nonexplosive homing vehicles, all of which would have to be stationed in low orbits.

The brightest laser beam attained so far is an infrared beam produced by a chemical laser that utilizes hydrogen fluoride. The U.S. Department of Defense plans to demonstrate a two-megawatt version of this laser by 1987. Assuming that 25-megawatt hydrogen-fluoride lasers and optically perfect 10-meter mirrors eventually become available, a weapon with a "kill radius" of 3,000 kilometers would be at hand. A total of 300 such lasers in low orbits could destroy 1,400 ICBM boosters in the absence of countermeasures if every component worked to its theoretical limit.

A particle-beam weapon could fire a stream of energetic charged particles, such as protons, that could penetrate deep into a missile and disrupt the semiconductors in its guidance system. A charged-particle beam, however, would be bent by the earth's magnetic field and therefore could not be aimed accurately at distant targets. Hence any plausible particle-beam weapon would have to produce a neutral beam, perhaps one consisting of hydrogen atoms (protons paired with oppositely charged electrons). This could be done, although aiming the beam would still present formidable problems. Interception would be possible only above the atmosphere at an altitude of 150 kilometers or more, since collisions with air molecules would disintegrate the atoms and the geomagnetic field would then fan out the beam. Furthermore, by using gallium arsenide semiconductors, which are about 1,000 times more resistant to radiation damage than silicon semiconductors, it would be possible to protect the missile's guidance computer from such a weapon.

Projectiles that home on the booster's flame are also under discussion. They have the advantage that impact would virtually guarantee destruction, whereas a beam weapon would have to dwell on the fast-moving booster for some time. Homing weapons, however, have two drawbacks that preclude their use as boost-phase interceptors. First, they move at less than .01 percent of the speed of light, and therefore they would have to be deployed in uneconomically large numbers. Second, a booster that burned out within the atmosphere would be immune to them, since friction with the air would blind their homing sensors.

That such a homing vehicle can indeed destroy an object in space was demonstrated by the U.S. Army in its current Homing Overlay test series. On June 10 a projectile launched from Kwajalein Atoll in the Pacific intercepted a dummy Minuteman warhead at an altitude of more than 100 miles. The interceptor relied on a homing technique similar to that of the Air Force's aircraft-launched antisatellite weapon. The debris from the collision was scattered over many tens of kilometers and was photographed by tracking telescopes [*see illustration on next two pages*]. The photographs show, among other things, the difficulty of evading a treaty that banned tests of weapons in space.

In an actual ballistic-missile-defense system such an interceptor might have a role in midcourse defense. It would have to be guided to a disguised reentry vehicle hidden in a swarm of decoys and other objects designed to confuse its infrared sensors. The potential of this technique for midcourse interception remains to be demonstrated, whereas its potential for boost-phase interception is questionable in view of the considerations mentioned above. On the other hand, a satellite is a larger and more fragile target than a reentry vehicle, and so the recent test shows the U.S. has a low-altitude antisatellite capability at least equivalent to the U.S.S.R.'s.

The importance of countermeasures in any consideration of ballistic-missile defense was emphasized recently by Richard D. DeLauer, Under Secretary of Defense for Research and Engineering. Testifying on this subject before the House Armed Services Committee, DeLauer stated that "any defensive system can be overcome with proliferation and decoys, decoys, decoys, decoys."

One extremely potent countermeasure has already been mentioned, namely that shortening the boost phase of the offensive missiles would nullify any boost-phase interception scheme based on X-ray lasers, neutral-particle beams or homing vehicles. Many other potent countermeasures that exploit existing technologies can also be envisioned. All of them rely on generic weaknesses of the defense. Among these weaknesses four stand out: (1) Unless the defensive weapons were cheaper than the offensive ones, any defense could simply be overwhelmed by a missile buildup; (2) the defense would have to attack every object that behaves like a booster; (3) any space-based defensive component would be far more vulnerable than the ICBM's it was designed to destroy; (4) since the booster, not the flame, would be the target, schemes based on infrared detection could be easily deceived.

Countermeasures can be divided into three categories: those that are threatening, in the sense of manifestly increasing the risk to the nation deploying the defensive system; those that are active, in the sense of attacking the defensive system itself, and those that are passive, in the sense of frustrating the system's weapons. These distinctions are politically and psychologically significant.

The most threatening response to a ballistic-missile-defense system is also the cheapest and surest: a massive buildup of real and fake ICBM's. The deployment of such a defensive system would violate the ABM Treaty, almost certainly resulting in the removal of all negotiated constraints on offensive missiles. Therefore many new missile silos could be constructed. Most of them could be comparatively inexpensive fakes arrayed in clusters about 1,000 kilometers across to exacerbate the satellites' absentee problem. The fake silos could house decoy ICBM's—boosters without expensive warheads or guidance packages—that would be indistinguishable from real ICBM's during boost phase. An attack could begin with a large proportion of decoys and shift to real ICBM's as the defense exhausted its weapons.

All space systems would be highly vulnerable to active countermeasures. Few targets could be more fragile than a large, exquisitely made mirror whose performance would be ruined by the slightest disturbance. If an adversary were to put a satellite into the same orbit as that of the antimissile weapon but moving in the opposite direction, the relative velocity of the two objects would be about 16 kilometers per second, which is eight times faster than that of a modern armor-piercing antitank projectile. If the satellite were to release a swarm of one-ounce pellets, each pellet could penetrate 15 centimeters of steel (and much farther if it were suitably shaped). Neither side could afford to launch antimissile satellites strong enough to withstand such projectiles. Furthermore, a large number of defensive satellites in low or geosynchronous orbits could be attacked simultaneously by "space mines": satellites parked in orbit near their potential victims and set to explode by remote control or when tampered with.

Passive countermeasures could be used to hinder targeting or to protect the booster. The actual target would be several meters above the flame, and the defensive weapon would have to determine the correct aim point by means of an algorithm stored in its computer. The aim point could not be allowed to drift by more than a fraction of a meter, because the beam weapon would have to dwell on one spot for at least several seconds as the booster moved several tens of kilometers. Aiming could therefore be impeded if the booster flame were made to fluctuate in an unpredictable way. This effect could be achieved by causing additives in the propellant to be emitted at random from different nozzles or by surrounding the booster with a hollow cylindrical "skirt" that could hide various fractions of the flame or even move up and down during boost phase.

Booster protection could take different forms. A highly reflective coating kept clean during boost phase by a strippable foil wrapping would greatly reduce the damaging effect of an incident laser beam. A hydraulic cooling system or a movable heat-absorbing ring could protect the attacked region at the command of heat sensors. Aside from shortening the boost phase the attacking nation could also equip each booster with a thin metallic sheet that could be unfurled at a high altitude to absorb and deflect an X-ray pulse.

Finally, as DeLauer has emphasized, all the proposed space weapons face formidable systemic problems. Realistic testing of the system as a whole is obviously impossible and would have to depend largely on computer simulation. According to DeLauer, the battle-management system would face a task of prodigious complexity that is "expected to stress software-development technology"; in addition it would have to "operate reliably even in the presence of disturbances caused by nuclear-weapons effects or direct-energy attack." The Fletcher panel's report states that the "*survivability of the system components is a critical issue whose resolution requires a combination of technologies and tactics that remain to be worked out.*" Moreover, nuclear attacks need not be confined to the battle-management system. For example, airbursts from a precursor salvo of SLBM's could produce atmospheric disturbances that would cripple an entire defensive system that relied on the ground-based laser scheme.

Spokesmen for the Reagan Administration have stated that the Strategic Defense Initiative will produce a shift to a "defense-dominated" world. Unless the move toward ballistic-missile defense is coupled with deep cuts in both sides' offensive forces, however, there will be no such shift. Such a coupling would require one or both of the following conditions: a defensive technology that was so robust and cheap that countermeasures or an offensive buildup would be futile, or a political climate that would engender arms-control agreements of unprecedented scope. Unfortunately neither of these conditions is in sight.

What shape, then, is the future likely to take if attempts are made by the U.S. and the U.S.S.R. to implement a space-based system aimed at thwarting a nuclear attack? Several factors will have a significant impact. First, the new technologies will at best take many years to develop, and, as we have argued, they will remain vulnerable to known countermeasures. Second, both sides are currently engaged in "strategic modernization" programs that will further enhance their already awesome offensive forces. Third, in pursuing ballistic-missile defense both sides will greatly increase their currently modest antisatellite capabilities. Fourth, the ABM Treaty, which is already under attack, will fall by the wayside.

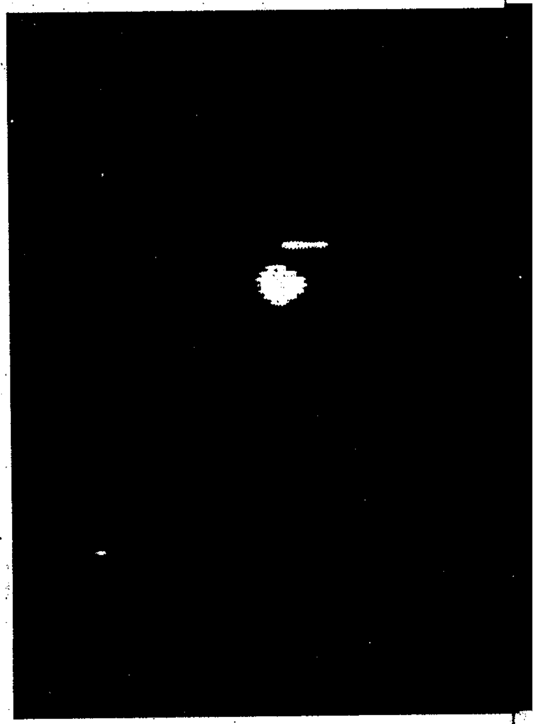
These factors, acting in concert, will accelerate the strategic-arms race and simultaneously diminish the stability of the deterrent balance in a crisis. Both superpowers have always been inordinately sensitive to real and perceived shifts in the strategic balance. A defense that could not fend off a full-scale strategic attack but might be quite effective against a weak retaliatory blow following an all-out preemptive strike would be particularly provocative. Indeed, the leaders of the U.S.S.R. have often stated that any U.S. move toward a comprehensive ballistic-missile-defense system would be viewed as an attempt to gain strategic superiority, and that no effort would be spared to prevent such an outcome. It would be foolhardy to ignore these statements.

The most likely Russian response to a U.S. decision to pursue the president's Strategic Defense Initiative should be expected to rely on traditional military "worst case" analysis; in this mode of reasoning one assigns a higher value to the other side's capabilities than an unbiased examination of the evidence would indicate, while correspondingly undervaluing one's own capabilities. In this instance the Russians will surely overestimate the effectiveness of the U.S. ballistic-missile defense and arm accordingly. Many near-term options would then be open to them. They could equip their large SS-18 ICBM's with decoys and many more warheads; they could retrofit their deployed ICBM's with protective countermeasures; they could introduce fast-burn boosters; they could deploy more of their current-model ICBM's and sea-launched cruise missiles. The latter developments would be perceived as unwarranted threats by U.S. military planners, who would be quite aware of the fragility of the nascent U.S. defensive system. A compensating U.S. buildup in offensive missiles would then be inevitable. Indeed, even if both sides bought identical defensive systems from a third party, conservative military analysis would guarantee an accelerated offensive-arms race.

Once one side began to deploy space-based antimissile beam weapons the level of risk would rise sharply. Even if the other side did not overrate the system's antimissile capability, it could properly view such a system as an immediate threat to its strategic satellites. A strategy of "launch on warning" might then seem unavoidable, and attempts might also be made to position space mines alongside the antimissile weapons. The last measure might in itself trigger a conflict since the antimissile system should be able to destroy a space mine at a considerable distance if it has any capability for its primary mission. In short, in a hostile political climate even a well-intentioned attempt to create a strategic defense could provoke war, just as the mobilizations of 1914 precipitated World War I.

Even if the space-based ballistic-missile defense did not have a cataclysmic birth, the successful deployment of such a defense would create a highly unstable strategic balance. It is difficult to imagine a system more likely to induce catastrophe than one that requires critical decisions by the second, is itself untested and fragile and yet is threatening to the other side's retaliatory capability.

In the face of mounting criticism Administration spokesmen have in recent months offered less ambitious rationales for the Strategic Defense Initiative than the president's original formulation.



**SUCCESSFUL INTERCEPTION of a ballistic-missile warhead was achieved on June 10 in the course of the U.S. Army's Homing Overlay Experiment. The target was a dummy warhead mounted on a Minuteman ICBM that was launched from Vandenberg Air Force Base in California. The interceptor was a nonexplosive infrared-homing vehicle that was**

One theme is that the program is just a research effort and that no decision to deploy will be made for many years. Military research programs are not normally announced from the Oval Office, however, and there is no precedent for a $26-billion, five-year military-research program without any commitment to deployment. A program of this magnitude, launched under such auspices, is likely to be treated as an essential military policy by the U.S.S.R. no matter how it is described in public.

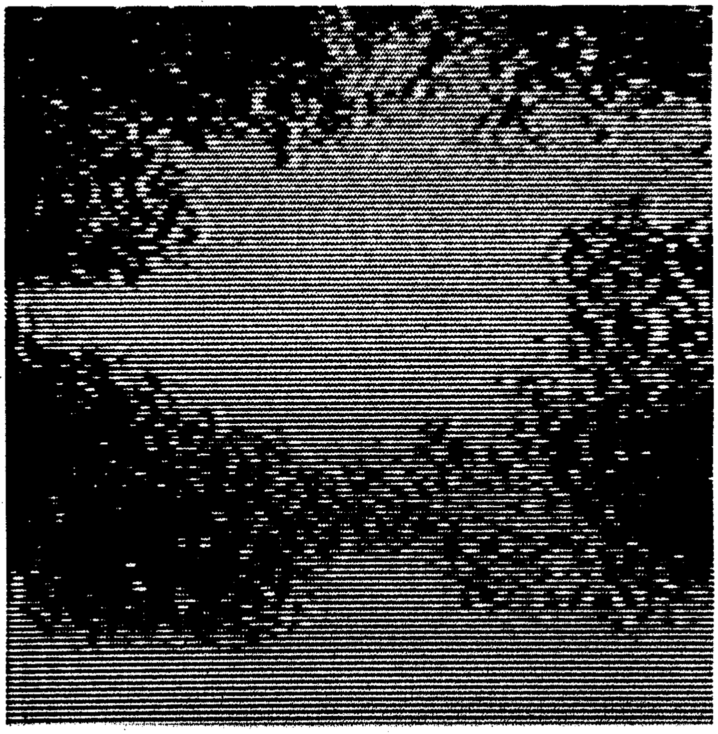
Another more modest rationale of the Strategic Defense Initiative is that it is intended to enhance nuclear deterrence. That role, however, would require only a terminal defense of hard targets, not weapons in space. Finally, it is contended that even an imperfect antimissile system would limit damage to the U.S.; the more likely consequence is exactly the opposite, since it would tend to focus the attack on cities, which could be destroyed even in the face of a highly proficient defense.

In a background report titled *Directed Energy Missile Defense in Space,* released earlier this year by the Congressional Office of Technology Assessment, the author, Ashton B. Carter of the Massachusetts Institute of Technology, a former Defense Department analyst with full access to classified data on such matters, concluded that "the prospect that emerging 'Star Wars' technologies, when further developed, will provide a perfect or near-perfect defense system... is so remote that it should not serve as the basis of public expectation or national policy." Based on our assessment of the technical issues, we are in complete agreement with this conclusion.

In our view the questionable performance of the proposed defense, the ease with which it could be overwhelmed or circumvented and its potential as an antisatellite system would cause grievous damage to the security of the U.S. if the Strategic Defense Initiative were to be pursued. The path toward greater security lies in quite another direction. Although research on ballistic-missile defense should continue at the traditional level of expenditure and within the constraints of the ABM Treaty, every effort should be made to negotiate a bilateral ban on the testing and use of space weapons.

It is essential that such an agreement cover all altitudes, because a ban on high-altitude antisatellite weapons alone would not be viable if directed-energy weapons were developed for ballistic-missile defense. Once such weapons were tested against dummy boosters or reentry vehicles at low altitude, they would already have the capability of attacking geosynchronous satellites without testing at high altitude. The maximum energy density of any such beam in a vacuum is inversely proportional to the square of the distance. Once it is demonstrated that such a weapon can deliver a certain energy dose in one second at a range of 4,000 kilometers, it is established that the beam can deliver the same dose at a range of 36,000 kilometers in approximately 100 seconds. Since the beam could dwell on a satellite indefinitely, such a device could be a potent weapon against satellites in geosynchronous orbits even if it failed in its ballistic-missile-defense mode.

As mentioned above, the U.S. interception of a Minuteman warhead over the Pacific shows that both sides now have a ground-based antisatellite weapon of roughly equal capability. Hence there is no longer an asymmetry in such antisatellite weapons. Only a lack of political foresight and determination blocks the path to agreement. Such a pact would not permanently close the door on a defense-dominated future. If unforeseen technological developments were to take place in a receptive international political climate in which they could be exploited to provide greater security than the current condition of deterrence by threat of retaliation provides, the renegotiation of existing treaties could be readily achieved.



launched 20 minutes later from Kwajalein Atoll in the western Pacific. This sequence of photographs was made from a video display of the interception recorded through a 24-inch tracking telescope on Kwajalein. The first frame shows the rocket plume from the homing vehicle a fraction of a second before its collision with the target above the atmosphere. The short horizontal bar above the image of the plume is a tracking marker. The smaller point of light at the lower left is a star. The second and third frames show the spreading clouds of debris from the two vehicles moments after the collision. Within seconds more than a million fragments were strewn over an area of 40 square kilometers. Just before the collision the homing vehicle had deployed a weighted steel "net" 15 feet across to increase the chances of interception; as it happened, the vehicle's infrared sensor guided it to a direct, body-to-body collision with the target. According to the authors, the test demonstrates that the U.S. now has a low-altitude antisatellite capability at least equivalent to that of the U.S.S.R.