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Anti-Ballistic-Missile Systems

The U.S. is now building a "light" ABM system. The authors argue that offensive tactics and cheap penetration aids could nullify the effectiveness of this system and any other visualized so far

by Richard L. Garwin and Hans A. Bethe

Last September, Secretary of Defense McNamara announced that the U.S. would build "a relatively light and reliable Chinese-oriented ABM system." With this statement he apparently ended a long and complex debate on the merits of any kind of anti-ballistic-missile system in an age of intercontinental ballistic missiles carrying multimegaton thermonuclear warheads. Secretary McNamara added that the U.S. would "begin actual production of such a system at the end of this year," meaning the end of 1967.

As two physicists who have been concerned for many years with the development and deployment of modern nuclear weapons we wish to offer some comments on this important matter. On examining the capabilities of ABM systems of various types, and on considering the stratagems available to a determined enemy who sought to nullify the effectiveness of such a system, we have come to the conclusion that the "light" system described by Secretary McNamara will add little, if anything, to the influences that should restrain China indefinitely from an attack on the U.S. First among these factors is China's certain knowledge that, in McNamara's words, "we have the power not only to destroy completely her entire nuclear offensive forces but to devastate her society as well."

An even more pertinent argument against the proposed ABM system, in our view, is that it will nourish the illusion that an effective defense against ballistic missiles is possible and will lead almost inevitably to demands that the light system, the estimated cost of which exceeds $5 billion, be expanded into a heavy system that could cost upward of $40 billion. The folly of undertaking to build such a system was vigorously stated by Secretary McNamara. "It is important to understand," he said, "that none of the [ABM] systems at the present or foreseeable state of the art would provide an impenetrable shield over the United States.... Let me make it very clear that the [cost] in itself is not the problem: the penetrability of the proposed shield is the problem."

In our view the penetrability of the light, Chinese-oriented shield is also a problem. It does not seem credible to us that, even if the Chinese succumbed to the "insane and suicidal" impulse to launch a nuclear attack on the U.S. within the next decade, they would also be foolish enough to have built complex and expensive missiles and nuclear warheads peculiarly vulnerable to the light ABM system now presumably under construction (a system whose characteristics and capabilities have been well publicized). In the area of strategic weapons a common understanding of the major elements and technical possibilities is essential to an informed and reasoned choice by the people, through their government, of a proper course of action. In this article we shall outline in general terms, using nonsecret information, the techniques an enemy could employ at no great cost to reduce the effectiveness of an ABM system even more elaborate than the one the Chinese will face. First, however, let us describe that system.

Known as the Sentinel system, it will provide for long-range interception by Spartan antimissile missiles and short-range interception by Sprint antimissile missiles. Both types of missile will be armed with thermonuclear warheads for the purpose of destroying or inactivating the attacker's thermonuclear weapons, which will be borne through the atmosphere and to their targets by reentry vehicles (RV's). The Spartan missiles, whose range is a few hundred kilometers, will be fired when an attacker's reentry vehicles are first detected rising above the horizon by perimeter acquisition radar (PAR).

If the attacker is using his available propulsion to deliver maximum payload, his reentry vehicles will follow a normal minimum-energy trajectory, and they will first be sighted by one of the PAR's when they are about 4,000 kilometers, or about 10 minutes, away [*see illustration on page 26*]. If the attacker chooses to launch his rockets with less than maximum payload, he can put them either in a lofted trajectory or in a depressed one. The lofted trajectory has certain advantages against a terminal defense system. The most extreme example of a depressed trajectory is the path followed by a low-orbit satellite. On such a trajectory a reentry vehicle could remain below an altitude of 160 kilometers and would not

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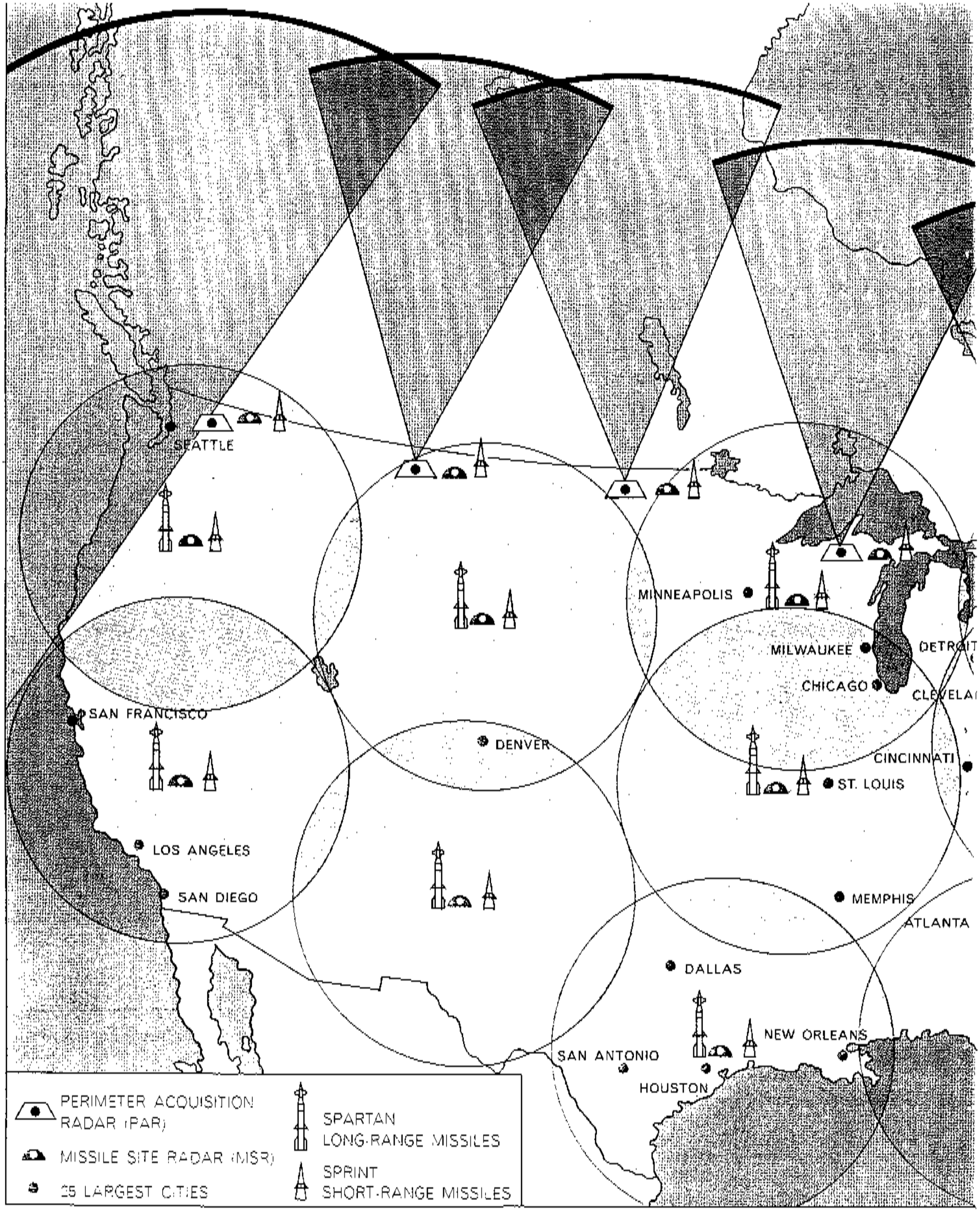
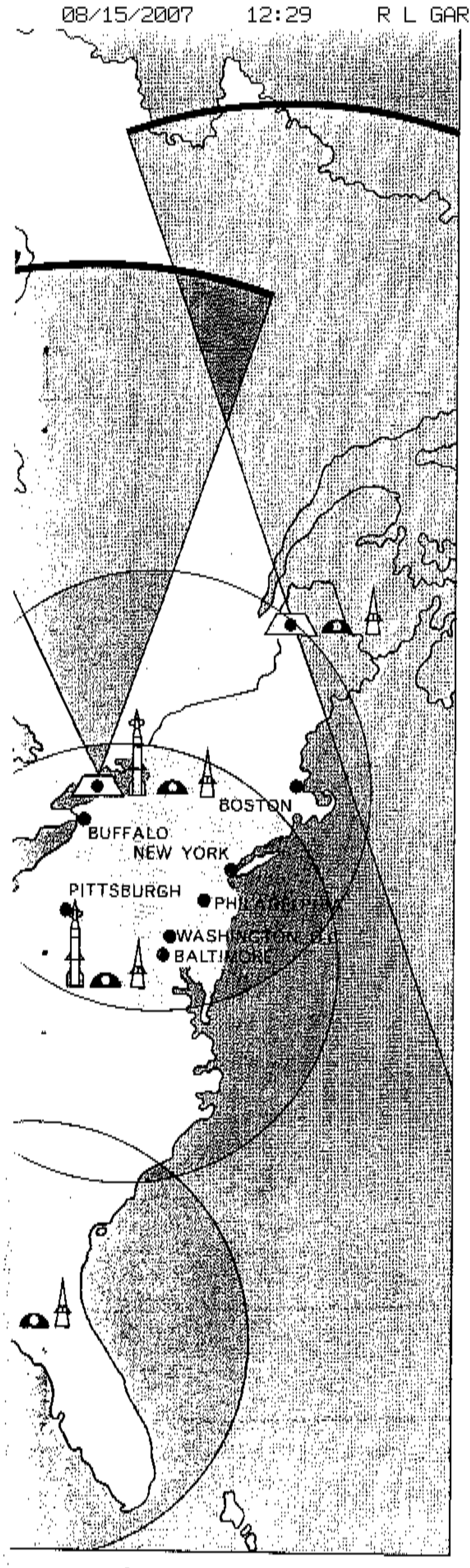


SENTINEL ANTI-BALLISTIC-MISSILE SYSTEM, described as a "relatively light and reliable Chinese-oriented ABM system," is now under construction at an estimated cost exceeding $5 billion. Designed to defend the entire U.S., Sentinel will depend on perhaps six perimeter acquisition radars (PAR's) along the country's borders to detect enemy missiles as they come over the northern horizon. The arcs at the end of the radar "fans" show where an enemy reentry vehicle (RV) would be detected if it were in a low, satellite-like orbit. The PAR's will alert Spartan interceptors located at some 10 or a dozen sites around the U.S. The sites shown on the map are not actual ones but indicate how the U.S. could be covered by a pattern of 10 Spartan sites, assuming that the Spar-



tans have an effective range of 600 kilometers. Each Spartan site will be protected by short-range Sprint missiles and will include missile-site radar (MSR) to help guide both types of missiles. Sprints and MSR's will also guard the PAR installations.

be visible to the horizon-search radar until it was some 1,400 kilometers, or about three minutes, away. This is FOBS: the fractional-orbit bombardment system, which allows intercontinental ballistic missiles to deliver perhaps 50 to 75 percent of their normal payload.

In the Sentinel system Spartans will be launched when PAR has sighted an incoming missile; they will be capable of intercepting the missile at a distance of several hundred kilometers. To provide a light shield for the entire U.S. about half a dozen PAR units will be deployed along the northern border of the country to detect missiles approaching from the general direction of the North Pole [*see illustration at left*]. Each PAR will be linked to several "farms" of long-range Spartan missiles, which can be hundreds of kilometers away. Next to each Spartan farm will be a farm of Sprint missiles together with missile-site radar (MSR), whose function is to help guide both the Spartans and the shorter-range Sprints to their targets. The task of the Sprints is to provide terminal protection for the important Spartans and MSR's. The PAR's will also be protected by Sprints and thus will require MSR's nearby.

Whereas the Spartans are expected to intercept an enemy missile well above the upper atmosphere, the Sprints are designed to be effective within the atmosphere, at altitudes below 35 kilometers. The explosion of an ABM missile's thermonuclear warhead will produce a huge flux of X rays, neutrons and other particles, and within the atmosphere a powerful blast wave as well. We shall describe later how X rays, particles and blast can incapacitate a reentry vehicle.

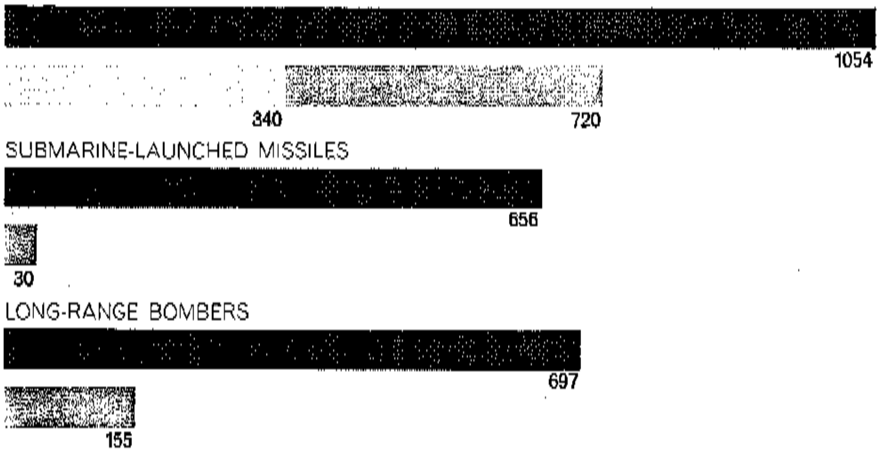
Before we consider in detail the capabilities and limitations of ABM systems, one of us (Garwin) will briefly summarize the present strategic position of the U.S. The primary fact is that the U.S. and the U.S.S.R. can annihilate each other as viable civilizations within a day and perhaps within an hour. Each can at will inflict on the other more than 120 million immediate deaths, to which must be added deaths that will be caused by fire, fallout, disease and starvation. In addition more than 75 percent of the productive capacity of each country would be destroyed, regardless of who strikes first. At present, therefore, each of the two countries has an assured destruction capability with respect to the other. It is usually assumed that a nation faced with the assured destruction of 30 percent of its population and productive capacity will be deterred from destroying another nation, no matter how serious the grievance. Assured destruction is therefore not a very flexible political or military tool. It serves only to preserve a nation from complete destruction. More conventional military forces are needed to fill the more conventional military role.

Assured destruction was not possible until the advent of thermonuclear weapons in the middle 1950's. At first, when one had to depend on aircraft to deliver such weapons, destruction was not really assured because a strategic air force is subject to surprise attack, to problems of command and control and to attrition by the air defenses of the other side. All of this was changed by the development of the intercontinental ballistic missile and also, although to a lesser extent, by modifications of our B-52 force that would enable it to penetrate enemy defenses at low altitude. There is no doubt today that the U.S.S.R. and the U.S. have achieved mutual assured destruction.

The U.S. has 1,000 Minuteman missiles in hardened "silos" and 54 much larger Titan II missiles. In addition we have 656 Polaris missiles in 41 submarines and nearly 700 long-range bombers. The Minutemen alone could survive a surprise attack and achieve assured destruction of the attacker. In his recent annual report the Secretary of Defense estimated that as of October, 1967, the U.S.S.R. had some 720 intercontinental ballistic missiles, about 30 submarine-launched ballistic missiles (excluding many that are airborne rather than ballistic) and about 155 long-range bombers. This force provides assured destruction of the U.S.

Secretary McNamara has also stated that U.S. forces can deliver more than 2,000 thermonuclear weapons with an average yield of one megaton, and that fewer than 400 such weapons would be needed for assured destruction of a third of the U.S.S.R.'s population and three-fourths of its industry. The U.S.S.R. would need somewhat fewer weapons to achieve the same results against the U.S.

It is worth remembering that intercontinental missiles and nuclear weapons are not the only means of mass destruction. They are, however, among the most reliable, as they were even when they were first made in the 1940's and 1950's. One might build a strategic force somewhat differently today, but the U.S. and the U.S.S.R. have no incentive for doing so. In fact, the chief virtue of assured destruction may be that it removes the need to race—there is no reward for



COMPARISON OF NUCLEAR WEAPON CARRIERS shows that the U.S. (*gray bars*) outweighs the U.S.S.R. in every category. These figures, representing U.S. intelligence estimates as of October 1, 1967, appear in the Secretary of Defense's latest annual report. The report notes that the number of Soviet ICBM's had increased from 340 a year earlier. Of the 1,054 U.S. ICBM's, 1,000 are Minutemen and 54 are Titan II's. The 30 submarine-launched ballistic missiles credited to the U.S.S.R. are believed to have a range considerably less than the range of some 2,500 kilometers for the 656 Polaris missiles aboard 41 nuclear-powered U.S. submarines. The report states that the combined U.S. force could deliver up to 4,500 nuclear warheads compared with about 1,000 larger warheads for the U.S.S.R. force.

getting ahead. One really should not worry too much about new means for delivering nuclear weapons (such as bombs in orbit or fractional-orbit systems) or about advances in chemical or biological warfare. A single thermonuclear assured-destruction force can deter such novel kinds of attack as well.

Now, as Secretary McNamara stated in his September speech, our defense experts reckoned conservatively six to 10 years ago, when our present strategic-force levels were planned. The result is that we have right now many more missiles than we need for assured destruction of the U.S.S.R. If war comes, therefore, the U.S. will use the excess force in a "damage-limiting" role, which means firing the excess at those elements of the Russian strategic force that would do the most damage to the U.S. Inasmuch as the U.S.S.R. has achieved the level of assured destruction, this action will not preserve the U.S., but it should reduce the damage, perhaps sparing a small city here or there or reducing somewhat the forces the U.S.S.R. can use against our allies. To the extent that this damage-limiting use of our forces reduces the damage done to the U.S.S.R. it may slightly reduce the deterrent effect resulting from assured destruction. It must be clear that only surplus forces will be used in this way. It should be said, however, that the exact level of casualties and industrial damage required to destroy a nation as a viable society has been the subject of surprisingly little research or even argument.

One can conceive of three threats to the present rather comforting situation of mutual assured destruction. The first would be an effective counterforce system: a system that would enable the U.S. (or the U.S.S.R.) to incapacitate the other side's strategic forces before they could be used. The second would be an effective ballistic-missile defense combined with an effective antiaircraft system. The third would be a transition from a bipolar world, in which the U.S. and the U.S.S.R. alone possess overwhelming power, to a multipolar world including, for instance, China. Such threats are of course more worrisome in combination than individually.

American and Russian defense planners are constantly evaluating less-than-perfect intelligence to see if any or all of these threats are developing. For purposes of discussion let us ask what responses a White side might make to various moves made by a Black side. Assume that Black has threatened to negate White's capability of assured destruction by doing one of the following things: (1) it has procured more intercontinental missiles, (2) it has installed some missile defense or (3) it has built up a large operational force of missiles each of which can attack several targets, using "multiple independently targetable reentry vehicles" (MIRV's).

White's goal is to maintain assured destruction. He is now worried that Black may be able to reduce to a dangerous level the number of White warheads that will reach their target.

threats—but not necessarily the most effective or the cheapest—is to provide himself with more launch vehicles. In addition, in order to meet the first and third threats White will try to make his launchers more difficult to destroy by one or more of the following means: by making them mobile (for example by placing them in submarines or on railroad cars), by further hardening their permanent sites or by defending them with an ABM system.

Another possibility that is less often discussed would be for White to arrange to fire the bulk of his warheads on "evaluation of threat." In other words, White could fire his land-based ballistic missiles when some fraction of them had already been destroyed by enemy warheads, or when an overwhelming attack is about to destroy them. To implement such a capability responsibly requires excellent communications, and the decision to fire would have to be made within minutes, leading to the execution of a prearranged firing plan. As a complete alternative to hardening and mobility, this fire-now-or-never capability would lead to tension and even, in the event of an accident, to catastrophe. Still, as a supplemental capability to ease fears of effective counterforce action, it may have some merit.

White's response to the second threat —an increase in Black's ABM defenses— might be limited to deploying more launchers, with the simple goal of saturating and exhausting Black's defenses. But White would also want to consider the cost and effectiveness of the following: penetration aids, concentrating on undefended or lightly defended targets, maneuvering reentry vehicles or multiple reentry vehicles. The last refers to several reentry vehicles carried by the same missile; the defense would have to destroy all of them to avoid damage. Finally, White could reopen the question of whether he should seek assured destruction solely by means of missiles. For example, he might reexamine the effectiveness of low-altitude bombers or he might turn his attention to chemical or biological weapons. It does not much matter how assured destruction is achieved. The important thing, as Secretary McNamara has emphasized, is that the other side find it credible. ("The point is that a potential aggressor must himself believe that our assured destruction capability is in fact actual, and that our will to use it in retaliation to an attack is in fact unwavering.")

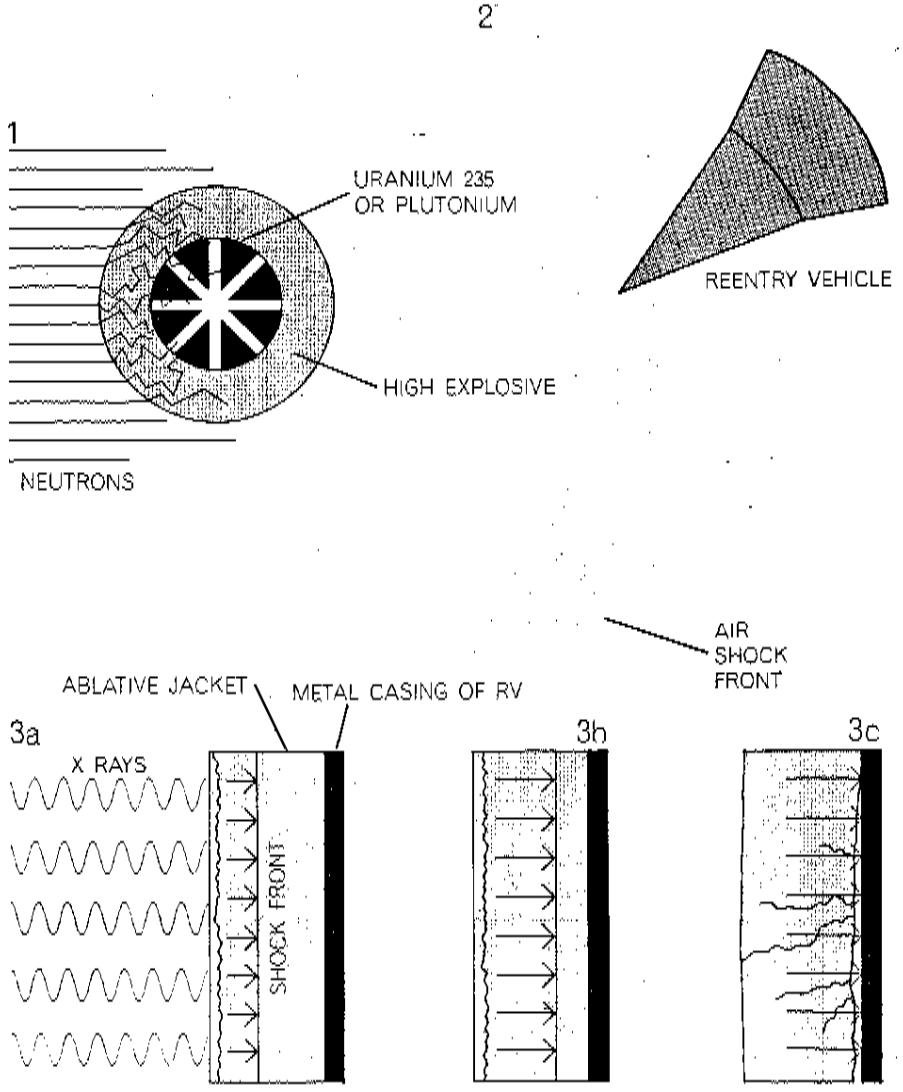
It is clear that White has many options, and that he will choose those that are most reliable or those that are cheapest for a given level of assured destruction. Although relative costs do depend on the level of destruction required, the important technical conclusion is that for conventional levels of assured destruction it is considerably cheaper for White to provide more offensive capability than it is for Black to defend his people and industry against a concerted strike.

As an aside, it might be mentioned that scientists newly engaged in the evaluation of military systems often have trouble grasping that large systems of the type created by or for the military are divided quite rigidly into several chronological stages, namely, in reverse order: operation, deployment, development and research. An operational system is not threatened by a system that is still in development; the threat is not real until the new system is in fact deployed, shaken down and fully operative. This is particularly true for an ABM system, which is obliged to operate against large numbers of relatively independent intercontinental ballistic missiles. It is equally true, however, for counterforce reentry vehicles, which can be ignored unless they are built by the hundreds or thousands. The same goes for MIRV's, a development of the multiple reentry vehicle in which each reentry vehicle is independently directed to a separate target. One must distinguish clearly between the *possibility* of development and the development itself, and similarly between development and actual operation. One must refrain from attributing to a specific defense system, such as Sentinel, those capabilities that *might* be obtained by further development of a different system.

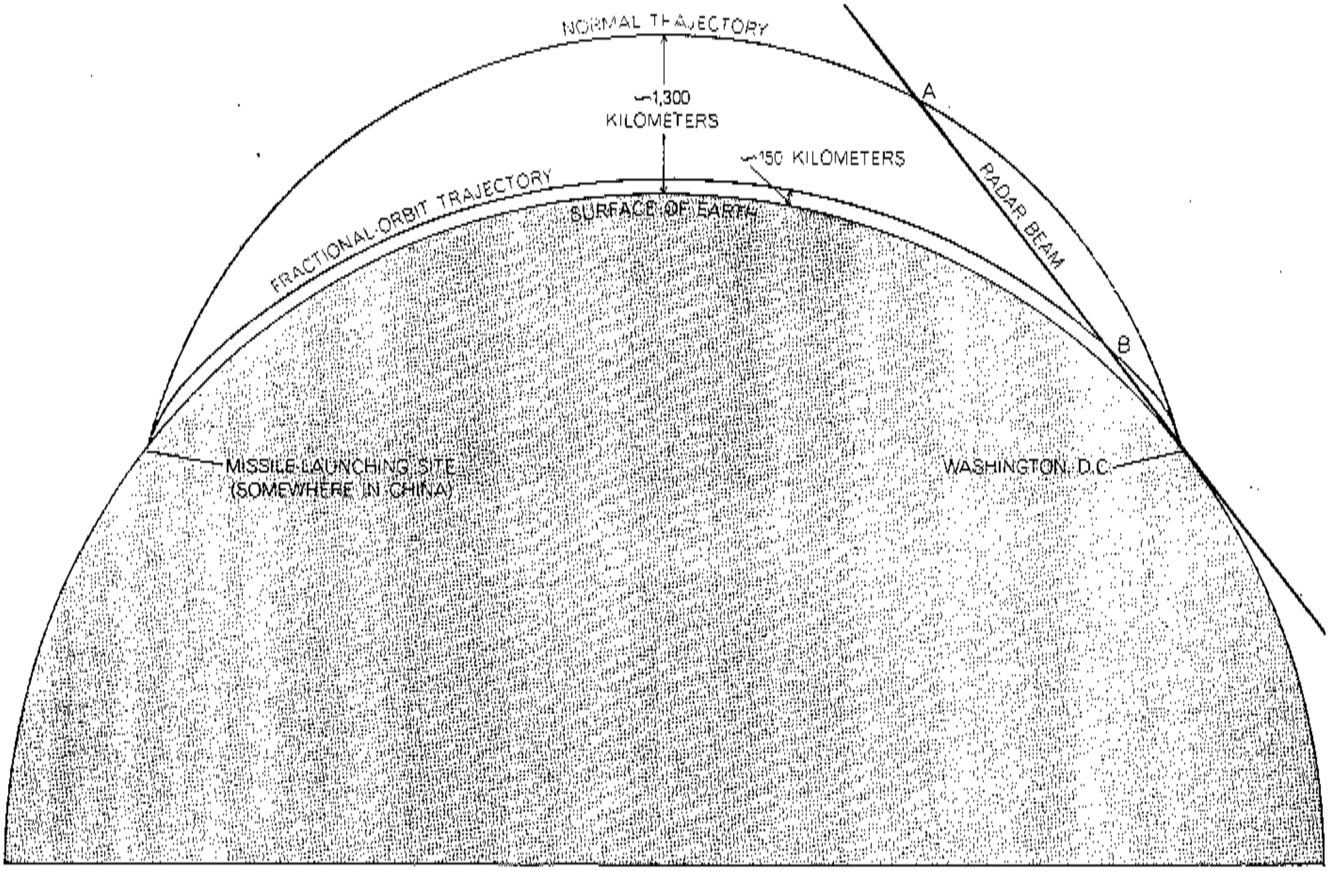
It follows that the Sentinel light ABM system, to be built now and to be operational in the early 1970's against a possible Chinese intercontinental ballistic missile threat, will have to reckon with a missile force unlike either the Russian or the American force, both of which were, after all, built when there was no ballistic-missile defense. The Chinese will probably build even their first operational intercontinental ballistic missiles so that they will have a chance to penetrate. Moreover, we believe it is well within China's capabilities to do a good job at this without intensive testing or tremendous sacrifice in payload.

Temporarily leaving aside penetration aids, there are two pure strategies for attack against a ballistic-missile defense. The first is an all-warhead attack in which one uses large booster rockets to transport many small (that is, fractional-megaton) warheads. These warheads are separated at some instant between the time the missile leaves the atmosphere and the time of reentry. The warheads from one missile can all be directed against the same large target (such as a city); these multiple reentry vehicles (MRV's) are purely a penetration aid. Alternatively each of the reentry vehicles can be given an independent boost to a different target, thus making them into MIRV's. MIRV is not a penetration aid but is rather a counterforce weapon: if each of the reentry vehicles has very high accuracy, then it is conceivable that each of them may destroy an enemy missile silo. The Titan II liquid-fuel rocket, designed more than 10 years ago, could carry 20 or more thermonuclear weapons. If these were employed simply as MRV's, the 54 Titans could provide more than 1,000 reentry vehicles for the defense to deal with.

Since the Spartan interceptors will each cost $1 million to $2 million, including their thermonuclear warheads, it is reasonable to believe thermonuclear warheads can be delivered for less than it will cost the defender to intercept them. The attacker can make a further relative saving by concentrating his strike so that most of the interceptors, all bought and paid for, have nothing to shoot at. This is a high-reliability penetration strategy open to any country that



MECHANISMS FOR KILLING REENTRY VEHICLES include the neutrons, blast and X radiation from a thermonuclear explosion. Neutrons (*1*) can penetrate the fission trigger of an enemy warhead, causing the uranium 235 or plutonium to melt and lose its shape. It can then no longer be assembled for firing. If the defensive warhead is fired inside the atmosphere, the resulting shock front of air (*2*) can cause the incoming reentry vehicle (RV) to decelerate with a force equivalent to several hundred times the force of gravity, thereby leading to its destruction or malfunction. If the explosion is outside the atmosphere, the X rays travel unimpeded to their target. On striking an RV (*3a*) they are absorbed by and intensely heat a thin layer of the RV's heat jacket. This creates a shock front that travels through the jacket (*3b, 3c*) and may cause the jacket to break up or detach from the RV.



MISSILE TRAJECTORIES can be chosen by the attacker to reduce the effectiveness of the defender's radar. The normal trajectory, which requires the least fuel, carries an ICBM to an altitude of about 1,300 kilometers. On its return to the earth the missile would intersect the path of a horizon-search radar at a distance of about 4,000 kilometers (*A*), when the missile was about 10 minutes away. Longer-range but less precise radars may be able to detect the missile earlier. On a fractional-orbit trajectory the missile would stay so close to the earth that it would not cross the radar horizon (*B*) until it was about 1,400 kilometers, or about three minutes, away.

can afford to spend a reasonable fraction of the amount its opponent can spend for defense.

The second pure strategy for attack against an ABM defense is to precede the actual attack with an all-decoy attack or to mix real warheads with decoys. This can be achieved rather cheaply by firing large rockets from unhardened sites to send light, unguided decoys more or less in the direction of plausible city targets. If the ABM defense is an area defense like the Sentinel system, it must fire against these threatening objects at very long range before they reenter the atmosphere, where because of their lightness they would behave differently from real warheads. Several hundred to several thousand such decoys launched by a few large vehicles could readily exhaust a Sentinel-like system. The attack with real warheads would then follow.

The key point is that since the putative Chinese intercontinental-ballistic-missile force is still in the early research and development stage, it can and will be designed to deal with the Sentinel system, whose interceptors and sensors are nearing production and are rather well publicized. It is much easier to design a missile force to counter a defense that is already being deployed than to design one for any of the possible defense systems that might or might not be deployed sometime in the future.

One of us (Bethe) will now describe (1) the physical mechanisms by which an ABM missile can destroy or damage an incoming warhead and (2) some of the penetration aids available to an attacker who is determined to have his warheads reach their targets.

Much study has been given to the possibility of using conventional explosives rather than a thermonuclear explosive in the warhead of a defensive missile. The answer is that the "kill" radius of a conventional explosive is much too small to be practical in a likely tactical engagement. We shall consider here only the more important effects of the defensive thermonuclear weapon: the emission of neutrons, the emission of X rays and, when the weapon is exploded in the atmosphere, blast.

Neutrons have the ability to penetrate matter of any kind. Those released by defensive weapons could penetrate the heat shield and outer jacket of an offensive warhead and enter the fissile material itself, causing the atoms to fission and generating large amounts of heat. If sufficient heat is generated, the fissile material will melt and lose its carefully designed shape. Thereafter it can no longer be detonated.

The kill radius for neutrons depends on the design of the offensive weapon and the yield, or energy release, of the defensive weapon. The miss distance, or distance of closest approach between the defensive and the offensive missiles, can be made small enough to achieve a kill by the neutron mechanism. This is particularly true if the defensive missile and radar have high performance and the interception is made no more than a few tens of kilometers from the ABM launch site. The neutron-kill mechanism is therefore practical for the short-range defense of a city or other important target. It is highly desirable that the yield of the defensive warhead be kept low to minimize the effects of blast and heat on the city being defended.

to shield the fissile material in the offensive warhead from neutron damage, but the mass of shielding needed is substantial. Witness the massive shield required to keep neutrons from escaping from nuclear reactors. The size of the reentry vehicle will enable the defense to make a rough estimate of the amount of shielding that can be carried and thus to estimate the intensity of neutrons required to melt the warhead's fissile material.

Let us consider next the effect of X rays. These rays carry off most of the energy emitted by nuclear weapons, especially those in the megaton range. If sufficient X-ray energy falls on a reentry vehicle, it will cause the surface layer of the vehicle's heat shield to evaporate. This in itself may not be too damaging, but the vapor leaves the surface at high velocity in a very brief time and the recoil sets up a powerful shock wave in the heat shield. The shock may destroy the heat shield material or the underlying structure.

X rays are particularly effective above the upper atmosphere, where they can travel to their target without being absorbed by air molecules. The defense can therefore use megaton weapons without endangering the population below; it is protected by the intervening atmosphere. The kill radius can then be many kilometers. This reduces the accuracy required of the defensive missile and allows successful interception at ranges of hundreds of kilometers from the ABM launch site. Thus X rays make possible an area defense and provide the key to the Sentinel system.

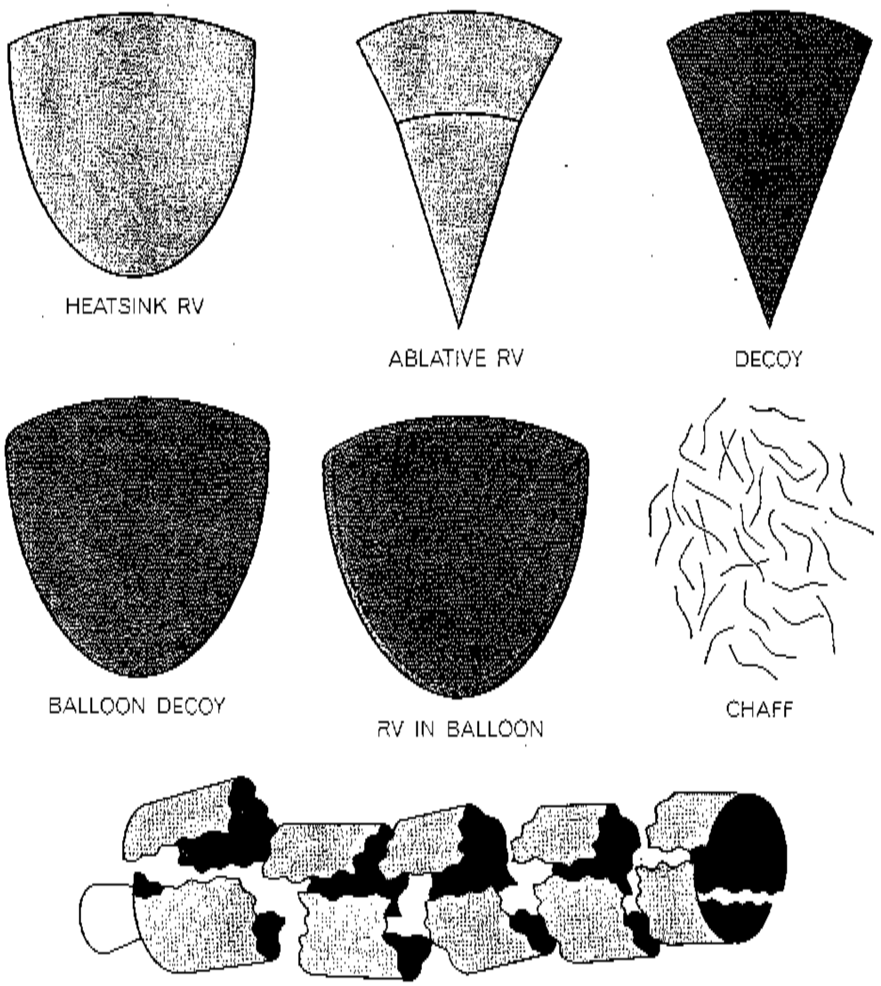
On the other hand, the reentry vehicle can be hardened against X-ray damage to a considerable extent. And in general the defender will not know if the vehicle has been damaged until it reenters the atmosphere. If it has been severely damaged, it may break up or burn up. If this does not happen, however, the defender is helpless unless he has also constructed an effective terminal, or short-range, defense system.

The third kill mechanism—blast—can operate only in the atmosphere and requires little comment. Ordinarily when an offensive warhead reenters the atmosphere it is decelerated by a force that, at maximum, is on the order of 100 *g*. (One *g* is the acceleration due to the earth's gravity.) The increased atmospheric density reached within a shock wave from a nuclear explosion in air can produce a deceleration several times greater. But just as one can shield against neutrons and X rays one can entry vehicle to have great structural strength. Moreover, the defense, not knowing the detailed design of the reentry vehicle, has little way of knowing if it has destroyed a given vehicle by blast until the warhead either goes off or fails to do so.

The main difficulty for the defense is the fact that in all probability the offensive reentry vehicle will not arrive as a single object that can be tracked and fired on but will be accompanied by many other objects deliberately placed there by the offense. These objects come under the heading of penetration aids. We shall discuss only a few of the many types of such aids. They include fragments of the booster rocket, decoys, fine metal wires called chaff, electronic countermeasures and blackout mechanisms of several kinds.

The last stage of the booster that has integrate into fragments or it can be fragmented deliberately. Some of the pieces will have a radar cross section comparable to or larger than the cross section of the reentry vehicle itself. The defensive radar therefore has the task of discriminating between a mass of debris and the warhead. Although various means of discrimination are effective to some extent, radar and data processing must be specifically set up for this purpose. In any case the radar must deal with tens of objects for each genuine target, and this imposes considerable complexity on the system.

There is, of course, an easy way to discriminate among such objects: let the whole swarm reenter the atmosphere. The lighter booster fragments will soon be slowed down, whereas the heavier reentry vehicle will continue to fall with essentially undiminished speed. If a swarm of objects is allowed to reenter,



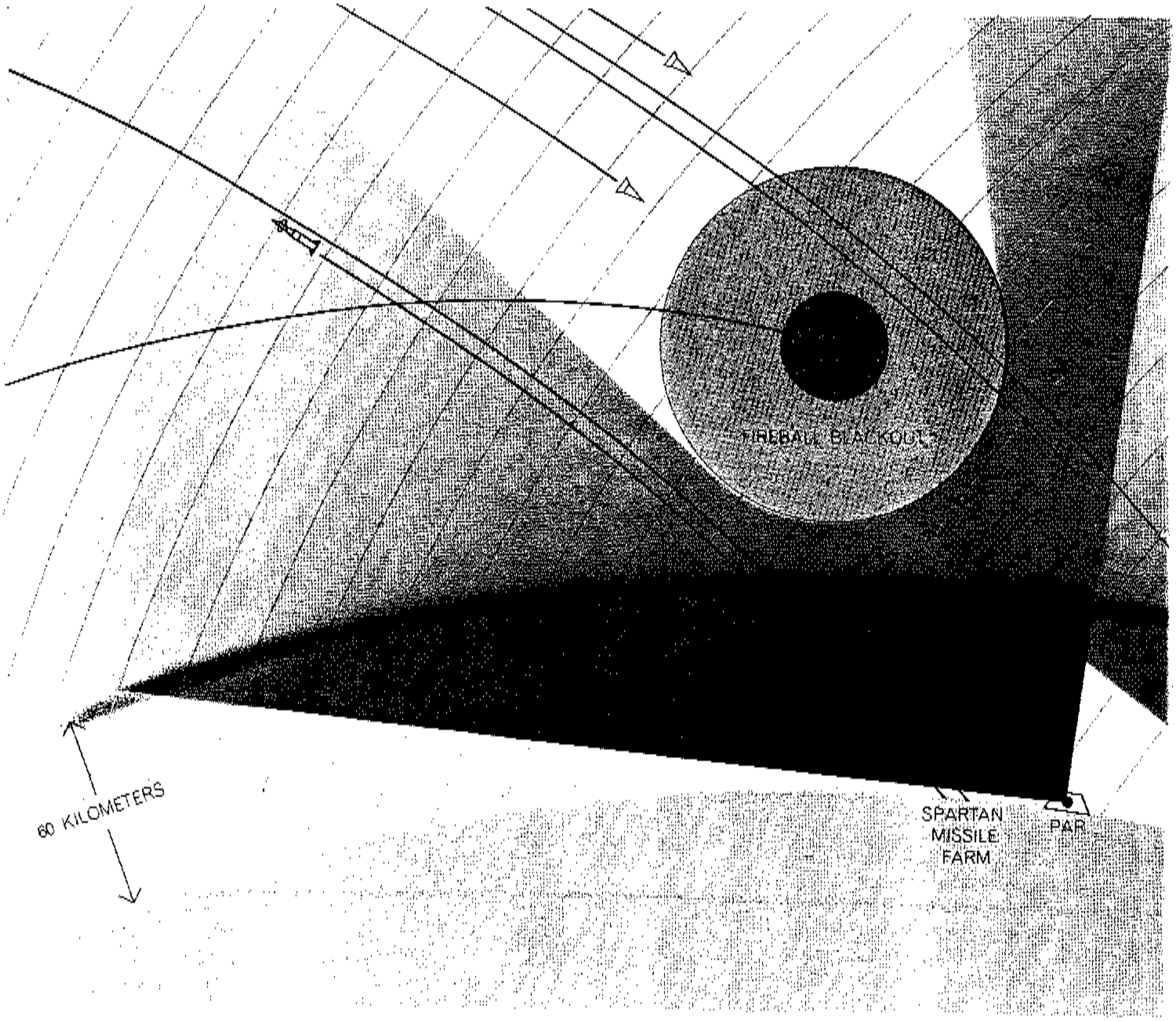
PENETRATION AIDS include objects that will reflect radar signals and thus simulate or conceal actual reentry vehicles (*color*). A decoy might be a simple conical structure or even a metallized balloon. RV's could be placed inside the same kind of balloon. Fragments of the launching vehicle and its fuel tank provide radar reflectors at no cost. Short bits of metal wire, called chaff, also make a cheap and lightweight reflector of radar signals.

ever, one must abandon the concept of area defense and construct a terminal defense system. If a nation insists on retaining a pure area defense, it must be prepared to shoot at every threatening object. Not only is this extremely costly but also it can quickly exhaust the supply of antimissile missiles.

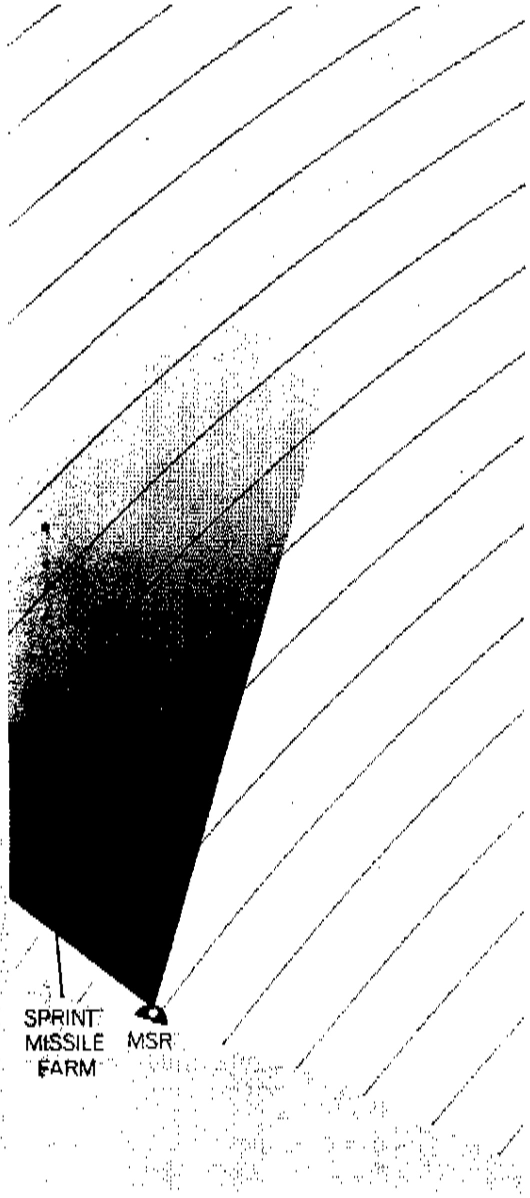
Instead of relying on the accidental targets provided by booster fragments, the offense will almost certainly want to employ decoys that closely imitate the radar reflectivity of the reentry vehicle. One cheap and simple decoy is a balloon with the same shape as the reentry vehicle. It can be made of thin plastic covered with metal in the form of foil, strips of wire mesh. A considerable number of such balloons can be carried uninflated by a single offensive missile and released when the missile has risen above the atmosphere.

The chief difficulty with balloons is putting them on a "credible" trajectory, that is, a trajectory aimed at a city or some other plausible target. Nonetheless, if the defending force employs an area defense and really seeks to protect the entire country, it must try to intercept every suspicious object, including balloon decoys. The defense may, however, decide not to shoot at incoming objects that seem to be directed against nonvital targets; thus it may choose to limit possible damage to the country rather than to avoid all damage. The offense could then take the option of directing live warheads against points on the outskirts of cities, where a nuclear explosion would still produce radioactivity and possibly severe fallout over densely populated regions. Worse, the possibility that reentry vehicles can be built to maneuver makes it dangerous to ignore objects even 100 kilometers off target.

Balloon decoys, even more than booster fragments, will be rapidly slowed by the atmosphere and will tend to burn up when they reenter it. Here again a terminal ABM system has a far better



RADAR BLACKOUTS can be created if enough free electrons are released in a sizable volume of space. An attacker can use thermonuclear explosions to generate the electrons required. A fireball blackout results when the heat from a nuclear explosion strips electrons from atoms and molecules of air. In this diagram a high-altitude fireball has been created by an enemy missile launched in a low orbit. The beta rays (electrons) released in the decay of fission products can create another type of blackout. If the beta rays are released at high altitude, they travel along the lines of force in the earth's magnetic field (*parallel colored lines*) and remove electrons from molecules in the atmosphere below. An effective beta blackout could be produced by spreading the fission products of a one-discriminate between decoys and warheads. One possibility for an area system is "active" discrimination. If a defensive nuclear missile is exploded somewhere in the cloud of balloon decoys traveling with a reentry vehicle, the balloons will either be destroyed by radiation from the explosion or will be blown far off course. The reentry vehicle presumably will survive. If the remaining set of objects is examined by radar, the reentry vehicle may stand out clearly. It can then be killed by a second interceptor shot. Such a shoot-look-shoot tactic may be effective, but it obviously places severe demands on the ABM missiles and



megaton explosion over an area 200 kilometers in radius. For several minutes the electron cloud would heavily absorb the long waves emitted by a PAR unit, here aimed to the north. The shorter MSR waves, however, would be attenuated only briefly.

can be countered by the use of small, dense decoys within the balloon swarms.

Moreover, it may be possible to develop decoys that are as resistant to X rays as the reentry vehicle and also are simple and compact. Their radar reflectivity could be made to simulate that of a reentry vehicle over a wide range of frequencies. The decoys could also be made to reenter the atmosphere—at least down to a fairly low altitude—in a way that closely mimicked an actual reentry vehicle. The design of such decoys, however, would require considerable experimentation and development.

Another way to confuse the defensive radar is to scatter the fine metal wires of chaff. If such wires are cut to about half the wavelength of the defensive radar, each wire will act as a reflecting dipole with a radar cross section approximately equal to the wavelength squared divided by 2π. The actual length of the wires is not critical; a wire of a given length is also effective against radar of shorter wavelength. Assuming that the radar wavelength is one meter and that one-mil copper wire is cut to half-meter lengths, one can easily calculate that 100 million chaff wires will weigh only 200 kilograms (440 pounds).

The chaff wires could be dispersed over a large volume of space; the chaff could be so dense and provide such large radar reflection that the reentry vehicle could not be seen against the background noise. The defense would then not know where in the large reflecting cloud the reentry vehicle is concealed. The defense would be induced to spend several interceptors to cover the entire cloud, with no certainty, even so, that the hidden reentry vehicle will be killed. How much of the chaff would survive the defensive nuclear explosion is another difficult question. The main problem for the attacker is to develop a way to disperse chaff more or less uniformly.

An active alternative to the use of chaff is to equip some decoys with electronic devices that generate radio noise at frequencies selected to jam the defensive radar. There are many variations on such electronic countermeasures, among them the use of jammers on the reentry vehicles themselves.

The last of the penetration aids that will be mentioned here is the radar blackout caused by the large number of free electrons released by a nuclear explosion. These electrons, except for a few, are removed from atoms or molecules of air, which thereby become ions. mation of ions; the fireball of the explosion, which produces ions because of its high temperature, and the radioactive debris of the explosion, which releases beta rays (high-energy electrons) that ionize the air they traverse. The second mechanism is important only at high altitude.

The electrons in an ionized cloud of gas have the property of bending and absorbing electromagnetic waves, particularly those of low frequency. Attenuation can reach such high values that the defensive radar is prevented from seeing any object behind the ionized cloud (unlike chaff, which confuses the radar only at the chaff range and not beyond).

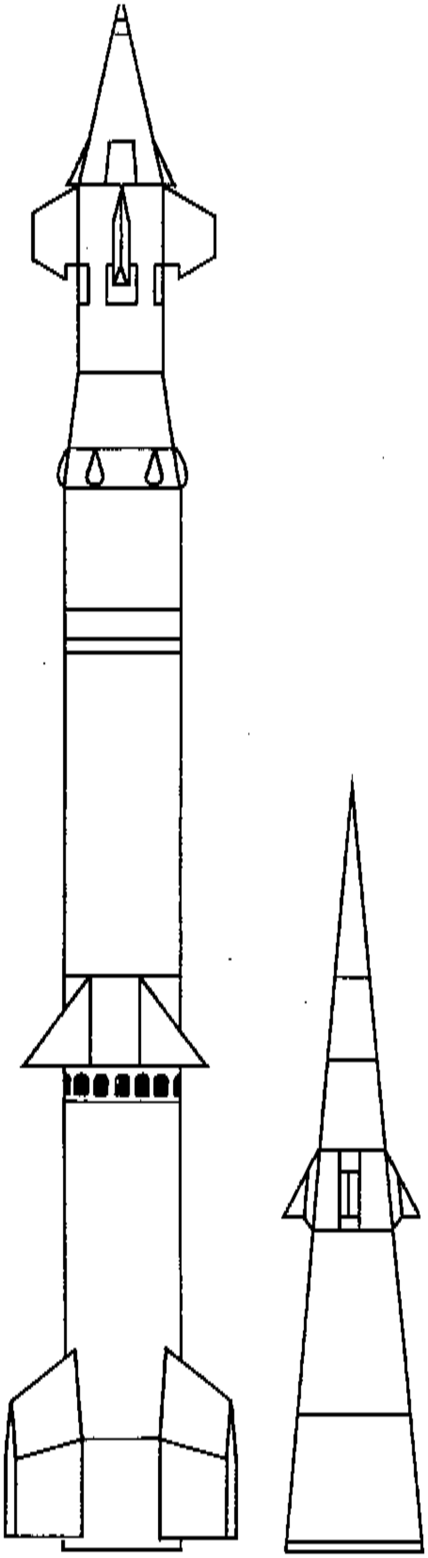
Blackout is a severe problem for an area defense designed to intercept missiles above the upper atmosphere. The problem is aggravated because area-defense radar is likely to employ low-frequency (long) waves, which are the most suitable for detecting enemy missiles at long range. In some recent popular articles long-wave radar has been hailed as the cure for the problems of the ABM missile. It is not. Even though it increases the capability of the radar in some ways, it makes the system more vulnerable to blackout.

Blackout can be caused in two ways: by the defensive nuclear explosions themselves and by deliberate explosions set off at high altitude by the attacker. Although the former are unavoidable, the defense has the choice of setting them off at altitudes and in locations that will cause the minimum blackout of its radar. The offense can sacrifice a few early missiles to cause blackout at strategic locations. In what follows we shall assume for purposes of discussion that the radar wavelength is one meter. Translation to other wavelengths is not difficult.

In order to totally reflect the one-meter waves from our hypothetical radar it is necessary for the attacker to create an ionized cloud containing 10^9 electrons per cubic centimeter. Much smaller electron densities, however, will suffice for considerable attenuation. For the benefit of technically minded readers, the equation for attenuation in decibels per kilometer is

$$\alpha = \frac{4.34}{3 \times 10^5} \frac{\omega_p^2}{\omega^2 + \gamma_c^2} \gamma_c \, .$$

Here ω_p is the plasma frequency for the given electron density, ω is the radar frequency in radians per second and γ_c is the frequency of collisions of an electron with atoms of air. At normal tempera-



SENTINEL MISSILES are the long-range Spartan (*left*), with a reported range of several hundred kilometers, and the Sprint (*right*), which will be used for terminal defense, usually below 35 kilometers. Both will be equipped with thermonuclear warheads designed to destroy or disable the attacker's bomb-carrying reentry vehicles. The Spartan, about 55 feet long, is a three-stage solid-fuel rocket. The smaller and faster Sprint missile uses two stages of solid fuel.

2×10^{11} multiplied by the density of the air (ρ) compared with sea-level density (ρ_0), or $\gamma_e = 2 \times 10^{11}\, \rho/\rho_0$. At altitudes above 30 kilometers, where an area-defense system will have to make most of its interceptions, the density of air is less than .01 of the density at sea level. Under these conditions the electron collision frequency γ_e is less than the value of $\omega = (2\pi \times 3 \times 10^8)$ and therefore can be neglected in the denominator of the equation. Using that equation, we can then specify the number of electrons, N_e, needed to attenuate one-meter radar waves by a factor of more than one decibel per kilometer: $N_e > 350\rho_0/\rho$. At an altitude of 30 kilometers, where ρ_0/ρ is about 100, N_e is about 3×10^4, and at 60 kilometers N_e is still only about 3×10^6. Thus the electron densities needed for the substantial attenuation of a radar signal are well under the 10^9 electrons per cubic centimeter required for total reflection. The ionized cloud created by the fireball of a nuclear explosion is typically 10 kilometers thick; if the attenuation is one decibel per kilometer, such a cloud would produce a total attenuation of 10 decibels. This implies a tenfold reduction of the outgoing radar signal and another tenfold reduction of the reflected signal, which amounts to effective blackout.

The temperature of the fireball created by a nuclear explosion in the atmosphere is initially hundreds of thousands of degrees centigrade. It quickly cools by radiation to about 5,000 degrees C. Thereafter cooling is produced primarily by the cold air entrained by the fireball as it rises slowly through the atmosphere, a process that takes several minutes.

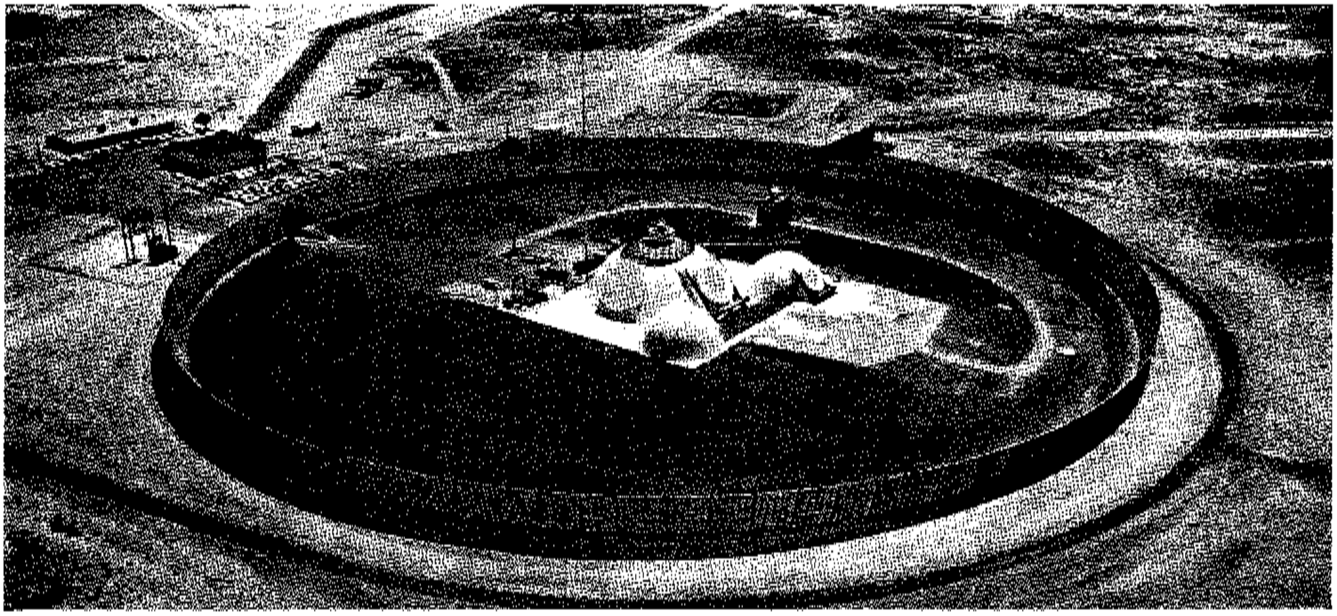
When air is heated to 5,000 degrees C., it is strongly ionized. To produce a radar attenuation of one decibel per kilometer at an altitude of 90 kilometers the fireball temperature need be only 3,000 degrees, and at 50 kilometers a temperature of 2,000 degrees will suffice. Ionization may be enhanced by the presence in the fireball of iron, uranium and other metals, which are normally present in the debris of nuclear explosion.

The size of the fireball can easily be estimated. Its diameter is about one kilometer for a one-megaton explosion at sea level. For other altitudes and yields there is a simple scaling law: the fireball diameter is equal to $(Y\rho_0/\rho)^{1/3}$, where Y is the yield in megatons. Thus a fireball one kilometer in diameter can be produced at an altitude of 30 kilometers (where $\rho_0/\rho = 100$) by an explosion of 10 kilotons, and at 50 kilometers (where $\rho_0/\rho = 1{,}000$), a one-megaton explosion will produce a fireball 10 kilometers in diameter. At still higher altitudes matters become complicated because the density of the atmosphere falls off so sharply and the mechanism of heating the atmosphere changes. Nevertheless, fireballs of very large diameter can be expected when megaton weapons are exploded above 100 kilometers. These could well black out areas of the sky measured in thousands of square kilometers.

For explosions at very high altitudes (between 100 and 200 kilometers) other phenomena become significant. Collisions between electrons and air molecules are now unimportant. The condition for blackout is simply that there be more than 10^9 electrons per cubic centimeter.

At the same time very little mass of air is available to cool the fireball. If the air is at first fully ionized by the explosion, the air molecules will be dissociated into atoms. The atomic ions combine very slowly with electrons. When the density is low enough, as it is at high altitude, the recombination can take place only by radiation. The radiative recombination constant (call it C_R) is about 10^{-12} cubic centimeter per second. When the initial electron density is well above 10^9 per cubic centimeter, the number of electrons remaining after time t is roughly equal to $1/C_R t$. Thus if the initial electron density is 10^{12} per cubic centimeter, the density will remain above 10^9 for 1,000 seconds, or some 17 minutes. The conclusion is that nuclear explosions at very high altitude can produce long-lasting blackouts over large areas.

The second of the two mechanisms for producing an ionized cloud, the beta rays issuing from the radioactive debris of a nuclear explosion, can be even more effective than the fireball mechanism. If the debris is at high altitude, the beta rays will follow the lines of force in the earth's magnetic field; with about half of the beta rays going immediately down into the atmosphere and the other half traveling out into space before returning earthward. These beta rays have an average energy of about 500,000 electron volts, and when they strike the atmosphere, they ionize air molecules. Beta rays of average energy penetrate to an altitude of about 60 kilometers; some of the more energetic rays go down to about 50 kilometers. At these levels, then, a high-altitude explosion will give



PROTOTYPE OF MISSILE-SITE RADAR is the multifunction array radar (MAR) at the Army's White Sands Missile Range in New Mexico. MSR, a smaller version of MAR, will be used to guide Spartans and Sprints to their targets. MAR provided an early demonstration that the fastest way to aim a radar beam at different parts of the sky is to switch the beam electronically.

rise to sustained ionization as long as the debris of the explosion stays in the vicinity.

One can show that blackout will occur if $y \times t^{1.2} > 10^{-2}$, where t is the time after the explosion in seconds and y is the fission yield deposited per unit horizontal area of the debris cloud, measured in tons of TNT equivalent per square kilometer. The factor $t^{1.2}$ expresses the rate of decay of the radioactive debris. If the attacker wishes to cause a blackout lasting five minutes ($t = 300$), he can achieve it with a debris level y equal to 10 tons of fission yield per square kilometer. This could be attained by spreading one megaton of fission products over a circular area about 400 kilometers in diameter at an altitude of, say, 60 kilometers. Very little could be seen by an area-defense radar attempting to look out from under such a blackout disk. Whether or not such a disk could actually be produced is another question. Terminal defense would not, of course, be greatly disturbed by a beta ray blackout.

The foregoing discussion has concentrated mainly on the penetration aids that can be devised against an area-defense system. By this we do not mean to suggest that a terminal-defense system can be effective, and we certainly do not wish to imply that we favor the development and deployment of such a system.

Terminal defense has a vulnerability all its own. Since it defends only a small area, it can easily be bypassed. Suppose that the 20 largest American cities were provided with terminal defense. It would be easy for an enemy to attack the 21st largest city and as many other undefended cities as he chose. Although the population per target would be less than if the largest cities were attacked, casualties would still be heavy. Alternatively the offense could concentrate on just a few of the 20 largest cities and exhaust their supply of antimissile missiles, which could readily be done by the use of multiple warheads even without decoys.

It was pointed out by Charles M. Herzfeld in *The Bulletin of the Atomic Scientists* a few years ago that a judicious employment of ABM defenses could equalize the risks of living in cities of various sizes. Suppose New York, with a population of about 10 million, were defended well enough to require 50 enemy warheads to penetrate the defenses, plus a few more to destroy the city. If cities of 200,000 inhabitants were left undefended, it would be equally "attractive" for an enemy to attack New York and penetrate its defenses as to attack an undefended city.

Even if such a "logical" pattern of ABM defense were to be seriously proposed, it is hard to believe that people in the undefended cities would accept their statistical security. To satisfy everyone would require a terminal system of enormous extent. The highest cost estimate made in public discussions, $50 billion, cannot be far wrong.

Although such a massive system would afford some protection against the U.S.S.R.'s present armament, it is virtually certain that the Russians would react to the deployment of the system. It would be easy for them to increase the number of their offensive warheads and thereby raise the level of expected damage back to the one now estimated. In his recent forecast of defense needs for the next five years, Secretary McNamara estimated the relative cost of ABM defenses and the cost of countermeasures that the offense can take. He finds invariably that the offense, by spending considerably less money than the defense, can restore casualties and destruction to the original level before defenses were installed. Since the offense is likely to be "conservative," it is our belief that the actual casualty figures in a nuclear exchange, after both sides had deployed ABM systems and simultaneously increased offensive forces, would be worse than these estimates suggest.

Any such massive escalation of offensive and defensive armaments could hardly be accomplished in a democracy without strong social and psychological effects. The nation would think more of war, prepare more for war, hate the potential enemy and thereby make war more likely. The policy of both the U.S. and the U.S.S.R. in the past decade has been to reduce tensions to provide more understanding, and to devise weapon systems that make war less likely. It seems to us that this should remain our policy.