Science & Global Security, 1998, Volume 7, pp. 333–360
Reprints available directly from the publisher
Photocopying permitted by license only

Bringing Prithvi Down to Earth: The Capabilities and Potential Effectiveness of India's Prithvi Missile

Z. Mian[a], A.H. Nayyar[b] and M.V. Ramana[c]

Prelude: The following paper was written prior to Pakistan's test of the Ghauri missile in April 1998 and also India and Pakistan's May 1998 nuclear weapon tests.

In recent years, the development, testing and ambiguous deployment status of India's short range Prithvi missile has caused great concern in Pakistan, and accelerated the missile race in South Asia. This paper summarizes the open literature descriptions of Prithvi and assesses the military effectiveness of Prithvi if it is used with conventional warheads in attacks on Pakistani airfields, command centers, and radar installations. It is shown that the current accuracy of Prithvi is such that a very large number of missiles would be needed to damage or destroy such targets. Given India's large air force, the small number of Prithvi missiles that have been ordered by India's armed forces, and the much larger number of missiles required to pose a significant additional military threat to Pakistan, the justification for Prithvi is obviously open to question. It is suggested that the induction of Prithvi with its present limited capabilities may be largely a result of institutional pressure from India's Defense Research and Development Organization, which is responsible for the missile program, rather than demand from the armed forces.

INTRODUCTION

The arms race between India and Pakistan has moved from their respective nuclear weapons capabilities[1] to the arena of ballistic missiles. A June 1997 report claimed India had moved a number of its indigenous Prithvi missiles to

a Visiting International Research Fellow, Union of Concerned Scientists, Cambridge, MA; Research Associate, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.
b Associate Professor, Department of Physics, Quaid-e-Azam University, Islamabad, Pakistan.
c SSRC-MacArthur Postdoctoral Fellow in International Peace and Security, Security Studies Program, Center for International Studies, Massachusetts Institute of Technology Cambridge, MA.

bases near the city of Jullunder close to the border with Pakistan.[2] While the Indian Prime Minister denied that Prithvi had been deployed and said the missiles had only been moved to a storage facility,[3] the government of Pakistan expressed its concern, with the Chief of Army Staff declaring Pakistan may proceed with the development of its own indigenous missile program.[4] In July 1997 there were reports of a test-firing of Pakistan's Hatf-3 missile, which is said to have a range of 600 km with a 250 kg warhead.[5] This was followed by statements that India was reviving its Agni Intermediate Range Ballistic Missile (IRBM) project and looking at a proposal for an integrated anti-missile defense program.[6] (On April 6, 1998 Pakistan tested what it claimed was a 1,500 km range missile named Ghauri.[7])

The tit-for-tat responses seem to take for granted the military utility of Prithvi and short-range ballistic missiles in general. This is despite strong evidence to the contrary. For example, a technical analysis of the possible role of Soviet tactical missiles as part of a non-nuclear pre-emptive strike on NATO air bases, air-defenses, command and control facilities, communications, and nuclear storage facilities showed that this threat was minor, unless hundreds if not thousands of missiles were used.[8] Similarly, historical experience of the use of such short-range missiles with conventional warheads suggests their effect has been "highly contingent [and] mitigated by their unreliability and inaccuracy, by targeting choices, geography, numbers, and an opponent's morale and ability to take countermeasures."[9]

In this paper we follow in the steps of these earlier studies and perform a technical evaluation of the effectiveness of using the Prithvi missile against Pakistan. The paper is structured as follows: in the following section, we describe some of the relevant characteristics of Prithvi. In the next section, we describe the damage caused by missiles armed with conventional warheads of the types proposed for Prithvi. In the following section, we assume that Prithvi will be used in a pre-emptive strike against Pakistani forces and capabilities that constitute the most serious threat to Indian forces and evaluate its military effectiveness. Our work suggests that if Prithvi is deployed with conventional warheads and used to attack military targets, its military utility would be marginal. We subsequently suggest some plausible reasons for India's continuation with the Prithvi program despite these drawbacks. We then draw some conclusions in the final section.

CHARACTERISTICS OF THE PRITHVI MISSILE

There are reported to be two versions of Prithvi,[10] with different payloads and ranges. Prithvi 1 to be deployed by the army, is said to carry a payload of 1,000 kg to a maximum range of 1,000 km, while Prithvi II, intended for the air force, carries a payload of 500 kg to a maximum range of 250 km. A third version with a 350 km range is also reported to be under development.[11] However, modeling of the missile suggests that this combination of ranges and payloads can be accommodated by one basic design, and that the two versions of Prithvi in fact use the same design with different warhead weights and thus different maximum ranges.[12] This model also suggests that the third version is likely to be the same design with a 250 kg payload.

Prithvi has a strap-down inertial guidance system,[13] and reportedly can be maneuvered by fins controlled by an on-board computer.[14] The Circular Error Probable (CEP)[15] of Prithvi is often given as 250 m.[16] This fits in with the rule of thumb (0.1 percent of the range) quoted for such short-range missiles with this kind of guidance. This is corroborated by another report which claims that Prithvi has a "proven accuracy of one meter to a kilometer," i.e., 0.1 percent.[17] Thus, at a maximum range of 250 km, Prithvi would have a CEP of 250 m. It is claimed that Prithvi is most likely to be used between ranges of 100–150 km,[18] and probably less than 200 km.[19] This would imply an operational CEP of about 100–200 m. It has been suggested, however, that more credible CEP estimates for Prithvi are 300 m at 150 km range and 500 m at 250 km range, i.e., 0.2 percent of the range.[20] A recent article suggests that a large fraction of Indian artillery officers also feel that Prithvi's accuracy under field conditions is likely to be closer to this latter value and this view is likely to form the doctrinal basis for its employment.[21] There have been reports that the Indian Defence Research and Development Organization (DRDO) plans to install the Global Positioning System (GPS) on the Prithvi to enhance its accuracy; DRDO claims that this would reduce the CEP to about 75 m.[22]

Prithvi is fuelled by a liquid propellant. According to most reports the oxidizer is inhibited red fuming nitric acid (IRFNA) and the fuel is a 50:50 combination of xylidine and tnethlyamine.[23] This combination is highly volatile and has to be loaded just prior to launch.

The first flight of Prithvi was on February 25, 1988.[24] Since then thirteen more tests of Prithvi I have been conducted.[25] These are reportedly largely successful except for the sixth test, during which the missile broke up in flight[26] when subjected to a high-G maneuver[27]—although another source claims the missile merely strayed from its flight path.[28] There have been two user trials by the Indian Army; the first, scheduled for May 13, 1994, was postponed because of a faulty nozzle in the fuel feed mechanism allowing fuel to leak into the engine casing. The user trials eventually took place on the 4th and 6th of June 1994. During these trials, the army is reported to have complained that changing the warhead on the Prithvi was difficult.[29] There has been only one test of the Prithvi II, which was conducted on January 27, 1996; no user trials have been held so far.[30]

Bharat Dynamics Limited is reported to be responsible for production of Prithvi, with serial production initially planned to begin in January 1991, at an annual production rate of 40–50 missiles.[31] But in September 1992, it was suggested that Bharat Dynamics "may fail to churn out the required numbers due to restrictions on some critical components."[32] It seems Prithvi has only been ready for production and deployment since June 1994.[33] It is significant, however, that the initial number of regiments commissioned to train with Prithvi was reduced from four to one, and that as of June 1994, the 333rd missile group, the military unit believed to have been trained and equipped with Prithvi, had an estimated stockpile of only 6 missiles.[34] Even in April 1995, it was reported that serial production of Prithvi had not stabilized and that Bharat Dynamics was manufacturing small arms for the Indian paramilitary forces due to lack of adequate orders for missiles.[35] A different estimate from the same time mentions a production rate of 3 missiles a month.[36] In July 1997, serial production of Prithvi was said to have been suspended.[37] A recent report mentions that the total inventory of Prithvi missiles that India possesses is 60.[38]

Prithvi is described as being deployed in missile regiments, each of which is to have four missile batteries, with a total of 16 missiles, along with four transporter-erector-launcher vehicles (TELS) and six support vehicles for maintenance, transport, fuels and communications.[39] However, perhaps only for the time being, the 333rd Missile Group seems to have a different deployment pattern. It is reported to be equipped with 12 TELs, grouped into three batteries of four TELS each.[40] Each battery is said to be equipped with a missile resupply/loading vehicle, a propellant tanker, a survey vehicle, and a firing command post.

The launch procedure is described as involving the transmission of target and a launch site information to a missile group, the missile being fuelled, and the TEL moving to the launch site and firing. The whole procedure is said to take from less than two hours,[41] up to three hours.[42] This seems comparable to the SCUD-B liquid fuelled missile which is said to require about 1–1.5 hours preparation time before it can be fired.[43]

Possible difficulties in removing liquid propellant from a missile's tanks and loading it back into a propellant tanker,[44] the loss of operational life that would follow from corrosion due to the small fraction of propellant that would be left over after unloading, and reports that once filled with propellant Prithvi only has a shelf life of 5 years,[45] would all inhibit the number of exercises involving actual propellant. It has been suggested that it is the concern about the liquid propellant and feed assembly that has delayed deployment of Prithvi, and that full deployment awaits a solid propellant version of the missile.[46]

According to most reports, the Prithvi is intended to be used with only conventional warheads.[47] There are said to be five such warheads; the standard high explosive unitary warhead, prefragmented, and cluster munitions,[48] an incendiary warhead, and possibly fuel air explosives.[49] The significance of the variety and type of warheads can be seen from their differing destructive capabilities against different kinds of targets[50] (discussed in the following section). There have been at least two tests of the warheads; a static test was carried out in March 1990 at the Pokharan range[51] and another test was carried out at Chandipur-at-Sea in June 1997.[52]

PRITHVI'S ABILITY TO INFLICT DAMAGE

A military target is said to be significantly damaged if it cannot be used for its intended purpose soon after an attack. For a target of a given hardness,[53] and a warhead with a given explosive power, one can define a certain length, known as the lethal radius (R_L), such that if the warhead explodes within a distance R_L of the target, the target will be significantly damaged. Clearly the lethal radius decreases with increasing hardness of target and decreasing yield (explosive power) of the warhead. Thus, the probability that a missile will significantly damage a target is a product of two factors: the probability that the missile arrives in the vicinity of the target intact and the probability that it detonates at a point which is at a distance R_L or less from the target. The first factor is the product of the probabilities of a successful launch, survival during flight and penetrating the defense. In the case of cluster warheads or fuel air explosives, the probability that the warhead will distribute its contents in the designed fashion should also be taken into account; we make the conservative assumption that this probability is unity. The second factor is called the kill probability and depends on the lethal radius of the target/warhead combination and the accuracy (CEP) of the missile. Written in symbolic terms:

$$\begin{aligned} \text{P(damage)} = \; & \text{P(launch)} \times \text{P(survival during flight)} \times \\ & \text{P(penetrating the defense)} \times \text{P(kill)} \end{aligned} \qquad (1)$$

The first component, P(launch), the probability of a successful launch, depends on the missile successfully being deployed in the field and going through its launch sequence. There are a number of factors that militate against Prithvi being successfully launched under battlefield conditions with 100 percent efficiency. Since it is deployed close to Pakistan—the current storage base at Jullunder is less than 100 km from the border—Prithvi batteries will be under observation, both through reconnaissance aircraft and spies, by Pakistan, especially during a crisis. The large retinue required, perhaps as many as four TELs and six other vehicles in each regiment, makes them vulnerable to preemptive attack, especially during the long fuelling time, if their location is known.

India's limited experience with the missile system adds to this vulnerability as well as creating separate grounds for launch failure. The use of liquid propellant is likely to be a particular problem. Apart from being highly corrosive and dangerous, liquid propellants require special fuel tanks, and complex fuel-injection systems involving high-pressure and high-speed pumps, high-pressure valves, regulators, joints and pipes, combustion chamber cooling, and ignition systems, all of which reduce reliability and require high maintenance.[54] Given that it is a new missile, it seems plausible to assume that Prithvi will also suffer from non-fuel related mechanical and other systems integration failures prior to take off.

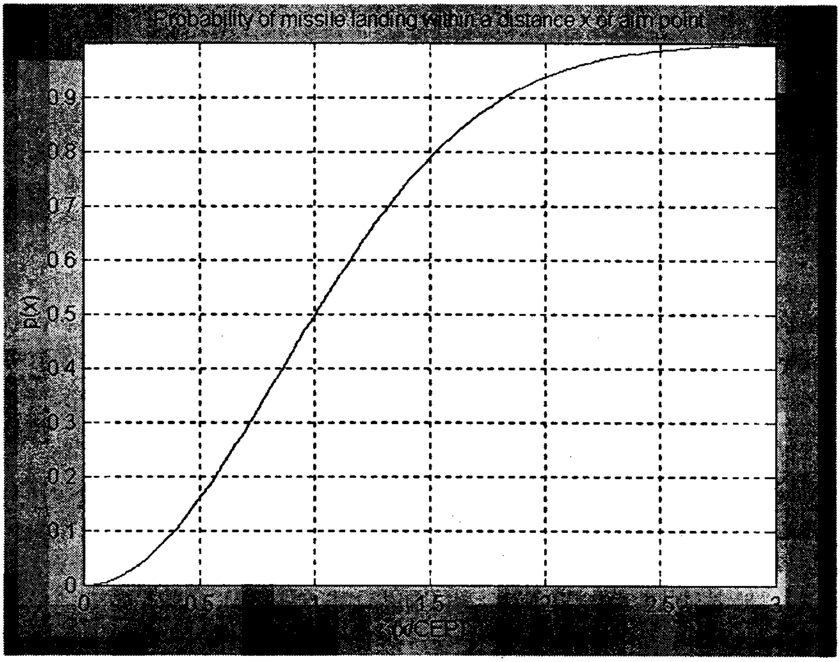
The second component of the probability of a missile damaging its target is a measure of how reliably the missile functions during flight once it has been launched. The break-up of Prithvi during the sixth test is an example of missile failure during flight. During the Gulf war, out of the 32 ATACM missiles launched by the US, at least one did not fly to its designed target. P(flight) has been estimated to range from 0.7 to 0.9 for Soviet tactical missiles.[55] The Soviet SS-N-4 which uses the same propellant as the Prithvi, was successful in 225 times out of 311 launches, i.e., a success rate of 0.72.[56] The naval version of the Soviet Scud-A was successful 59 times out of 77 launches and the SS-N-5 was successful 193 times out of 228 launches. Given the similarities between the Prithvi and the Soviet SCUD-B, an estimate of 0.7 to 0.9 may well be applicable to the Prithvi as well. It is worth noting however that while P(flight) depends in large part on the design and flight testing of the missile, the larger the number of tests the more likely it is that all the systems will function as intended. The limited number of flight tests of Prithvi—so far only fifteen have been reported—suggests that reliability may be a greater problem than with Soviet missiles.

The absence of any kind of anti-ballistic missile system in Pakistan, and the inadequacy of such systems even when they are present,[57] suggests that the third component of the probability, that a missile will successfully penetrate any defenses around the target, can safely be assumed to be unity.[58]

Based on these reasons, we assume that the product of the first three factors is about 0.8.

The remaining piece, P(kill), is the probability that the missile lands within a distance R_L of the target. In general, the probability of a missile (that survives launch, flight etc.) landing within a distance X of the aim point[59] is given by:

$$P(X) = 1 - 0.5^{\left(\frac{X}{CEP}\right)^2} \qquad (2)$$



This depends only on the accuracy (CEP) of the missile. It assumes that the location of the target and launch points are known precisely. If any of these are not known precisely, then one can assign an error (δ) to it as well and define a new effective CEP as follows:

$$CEP_{eff} = \sqrt{(CEP^2 + \delta_{target}{}^2 + \delta_{launch}{}^2)} \qquad (3)$$

There are good reasons to believe that δ_{launch} and especially δ_{target} are not insignificant. Measuring δ_{launch} at the time of firing accurately may be difficult and could increase the vulnerability of the forces. One alternative is to fire from pre-surveyed sites. This restricts the choices available to the missile forces and Pakistan could watch these sites on a continuous basis; again, this clearly increases vulnerability.[60] If, however, a GPS receiver is used by the launch crew, this problem can be solved. But it would not have any significant effect on δ_{target}; in view of India's limited intelligence gathering abilities this may be considerable except in the case of large static targets like above ground command centers and runways. We take this uncertainty into account by calculating our results for a range of CEP values.

R_L depends on the explosive yield, type of warhead, and the target dimensions and hardness and we will calculate it later for different kinds of targets and warheads. Once the lethal radius has been calculated, the kill probability is obtained by substituting R_L for X in Equation 2.

Now we consider the different kinds of warheads that Prithvi may use. As mentioned earlier Prithvi is reported as having five possible warheads, all loaded with conventional explosives.

In unitary warheads, the destructive power is intense but localized, with the explosive effect falling off rapidly with the distance (very approximately as the cubic power of the distance) and the radius of damage increasing slowly (very approximately as the cube root) with increasing weight of explosive.[61] This is the most common variety of warhead and is best suited to heavily fortified targets which require large overpressures to damage. However, as we will demonstrate, since Prithvi's CEP is large compared to the lethal radius of hardened structures, a large number of missiles with unitary warheads may be required to ensure destruction of such targets.

In pre-fragmented warheads there is a high ratio of metal fragments to explosive. This implies that a portion of the energy of the explosive is carried away as kinetic energy of these fragments instead of the blast wave. This increases the distance to which the effects of the explosion are carried, but only in the direction in which these fragments travel. Thus, the target is not evenly damaged.[62] Further, when compared to a unitary warhead, the smaller amount of explosive means each fragment travels at a lower velocity. Such warheads are not likely to be effective against hardened targets or heavily armored vehicles. Their chief utility is against troops in the field.

The third kind of warhead reportedly available for Prithvi is a cluster munition. This kind of warhead is composed of a number of smaller sub-munitions that are dispersed before they explode. The sub-munitions can themselves be high-explosives, pre-fragmentation, incendiary, and so on. Theoretically, a warhead with N equally heavy sub-munitions, which are uniformly distributed, could subject an area that could be up to $(N)^{1/3}$ times as large as the area subjected to the same overpressure by a unitary warhead. In practice the area is smaller due to the decrease in explosive power lost in adding the necessary individual casings, fuses, and so on. Nevertheless, this type of warhead, if it functions in the manner described, i.e., spreads and detonates all the sub-munitions uniformly, could compensate somewhat for poor accuracy and are most useful against relatively soft and spread out targets like field troops, airfields, and radar stations.

Designing warheads with cluster munitions is not easy. One major problem relates to the ability of the missile to spread sub-munitions evenly within a well determined radius, usually termed the radius of dispersal. This requires a precise mechanism for distribution. This requirement leads to further inclusion of non-explosive components in the missile warhead, lowering the amount of explosive power that can be delivered. These also lead to separate possibilities for the missile or warhead not performing in the manner intended.

Incendiary warheads can be used to set off large scale fires, but this requires the use of large numbers of such warheads, usually as large aircraft-carried bombs.[63] It has limited military utility and its primary use is as a weapon of terror in urban areas.

Fuel air explosives disperse an explosive aerosol that is then detonated by a delayed fuse. While this covers a large area, the overpressures achieved by such explosives are much lower. Hence, gravity bombs utilizing such explosives have been mainly used, for example in the Vietnam war, as anti-personnel weapons, and possibly in mine clearing.[64] When used in ballistic missile warheads that are traveling much faster than sound, there are enormous technically difficulties in making this technology work.[65] One demanding constraint, for example, is that the fuel-air mixture is explosive only within a limited range of concentrations.[66] In fact, early versions of fuel air explosives were designed to be delivered by helicopters and slow fixed-wing airplanes which could deliver the bomb at low speeds. Thus, the difficulties in making this technology work, in combination with the low overpressures achieved, limit the value of this technology for a missile warhead,[67] and we do not consider its use with Prithvi. Indeed, most reports only mention that the DRDO is in the process of developing fuel air explosives rather than being ready for use.

For reasons mentioned above, we do not consider the effects of fuel-air explosives, incendiary or pre-fragmented warheads.

MILITARY UTILITY OF PRITHVI

There are numerous descriptions of Prithvi's intended use in the open literature. An early report mentions using high explosive (conventional) warheads for "destroying troop concentrations, crippling air-bases, (and) striking at large static (military) installations and headquarters."[68] While it is impossible to know what targets will be attacked, there are reasons for accepting that there will be an emphasis on such targets rather than communication systems, ammunition dumps, railroad junctions, and even power stations, gas and oil installations and oil tank parks—all of which are also mentioned as possible targets for Prithvi.[69] A recent RAND study suggests a war in South Asia will probably be short, lasting two to three weeks, and therefore targeting infrastructure would be "extremely costly and may be relatively unproductive" and that the minimal strategic targets are "more operational-warfighting-assets."[70] Similarly, it has been claimed that at the onset of war the "top priority" of Indian military planners would be to destroy Pakistan's airbases, and thus render ineffective Pakistan's nuclear weapons delivery systems.[71]

The experience of the 1965 and 1971 India-Pakistan wars would seem to support such suggestions. In 1965, it seems air power was used largely to support ground forces, with limited attempts at attacking airfields, while in 1971 there were attacks on oil and rail facilities as well as on major Pakistani cities, once Indian forces gained air superiority.[72]

We assume that nuclear installations will not be targeted based on the 1988 agreement between India and Pakistan not to attack each other's nuclear facilities.

To our knowledge, there are no public statements claiming that Prithvi will be used with a non-conventional warhead. In line with our procedure in the rest of this analysis, we will assume this to be true and calculate the expected damage only from conventional warheads described earlier. The use of chemical or biological weapons is also unlikely if one assumes that India will adhere to the Chemical and Biological Weapons Conventions, both of which it has signed and ratified.

On this basis we try to calculate the total numbers of missiles needed to damage all the intended targets in some categories, namely airfields, command centers, and air defense radar. If this were accomplished, it would help achieve air superiority for India.

In order to account for the spread in accuracy quoted in various references and for future improvements, we assume a range of values for Prithvi's CEP: 50, 100, 150, 250, 300 m. As mentioned earlier, this will also account for some inaccuracies in knowing the exact location of the target due to the limited means for intelligence gathering available to the Indian army. For each of those values, we calculate the numbers of Prithvi missiles needed to effectively disable the three classes of targets, i.e., runways in airbases, command centers and bunkers, and stationary raiders. In each case, we will just list the smallest numbers, i.e., assuming the most optimistic performance on the part of Prithvi. We will also assume that all the targets are attacked by 1,000 kg warheads rather than 500 kg. This, again, will only under-estimate the number of Prithvis needed.

Given the accuracy that Prithvi is capable of, it does not make sense to attack relatively soft targets like radar and aircraft runways with unitary warheads. The radius to which a 1,000 kg warhead can damage 10 psi targets is about 35 m. Instead, if a cluster warhead with about 100 submunitions per warhead lands on the target, one can saturate a larger area provided the submunitions are distributed uniformly within an optimized spread radius. For example, choosing a spread radius of 60 m, the probability that any 10 psi target within this circle will be damaged is over 0.8.

On the other hand, unitary warheads may be the most effective when it comes to damaging a small hardened target, such as command posts or aircraft shelters; cluster munitions are relatively ineffective for this purpose. The lethal radius for a 10 kg cluster munition for even a 40 psi target—about 3 m—is much smaller than the size of a typical hardened structure. The chosen requirement of 40 psi corresponds to the overpressure needed to demolish a typical unreinforced building. However, it would probably not be able to destroy a reinforced concrete and steel building, such as an aircraft hangar or an above ground bunker.[73] In choosing this low requirement for overpressure we are overestimating the capabilities of Prithvi warheads. It is difficult to ensure that several submunitions would hit the same target since munitions tend to spread due to their high velocities: this implies that only a small portion of the structure could be damaged at best.

AIRFIELDS

A map in *International Defense Review* (Vol. 8, 1995) shows the following Pakistani cities and airbases within 250 km of the Indian border: Karachi, Badin, Malir, Hyderabad, Larkana, Sukkur Bahawalpur, D.G. Khan, Multan, Faisalabad, Jhang, Lahore, Sarghoda, Gujranwala, Sialkot. Rawalpindi, Islamabad, Nowshera/Risalpur, Peshawar, Abbotabad, and Mardan. Another article also lists the "crucial airbases in Kamra and Chaklala" as being within the range of Prithvi-I.[74] There are 10 air fields and 7 civilian airports within this range, all of which would have to be significantly damaged in order to "cripple" Pakistan's air force capability.

In order to disable an airfield so that no planes can take off or land, one has to make sure that no usable stretch of runway is available. The most effective way to do this would be to use special runway penetrating bombs which would explode after penetrating the surface, thus maximizing the damage to the runway. If successful, it could take several days to repair runways after such underground explosions since one has to make sure that there are no craters beneath the surface. When such bomblets are delivered by ballistic missiles, in order to survive the high speed of impact with the runway, explosives would have to be heavily armored. Further, given the high speed with which the munitions arrive, the angle between the warhead or munitions and the ground should be within a limited range of angles so as not to ricochet. If cluster munitions are used, this requirement again constrains designers to use heavy metal in each of the munitions, so as to lower the center of gravity and thus forcing the munitions to land on one side preferentially. Both these requirements lower the weight of the actual quantity of explosive delivered. We, therefore, assume that only 70 sub-munitions, each carrying about 10 kg of HE, is delivered by a Prithvi warhead.

Since a missile attack would be expected to be followed by further air or missile attacks, it would be safe to assume that pilots at the attacked airfields will try to take off in the shortest possible distance using each and every available runway strip as soon as possible. Modern fighters, with their high maneuver and acceleration capabilities, bring down the requirements for available runway lengths tremendously. Pakistan relies on US-made F-16 and French-made Mirage airplanes for its front-line aircraft. Those typically need less than 400 m in length,[75] and less than 10 m in width[76] of runway to take off. This means that a typical runway, which we assume to be over 1.5 km long and 50 m wide, could be said to contain about 20 strips, each of which is sufficiently long and wide for a plane to take off. All those strips have to be damaged by the missile attack. This is best done with sub-munitions since they create many small craters which are sufficient to deny that section of the runway to military use; a unitary warhead, on the other hand, would create one large crater, which planes may be able to avoid more easily. So we assume that cluster munitions are used with an optimized dispersal radius. This dispersal radius is typically greater than 50 m; hence, it is most efficient to attempt to damage the whole width of a runway with one warhead than to aim a warhead for every strip of width 10 m.

For each CEP, using the procedure outlined in the appendix, we first calculate P(kill) the probability of damaging a strip of length 400 m and 50 m width sufficiently to render it unfit for airplanes taking off. Now, we incorporate the factor of 0.8—the assumed probability of a successful launch, surviving the flight, penetrating defenses and distributing its submunitions in the expected fashion—to calculate P(damage). Since these are typically quite small, in order to ensure a high probability of damage to the runway, several missiles would have to be launched at each strip. The number of missiles required to damage a strip with a probability of P(confidence) or higher is:

$$\text{N(missiles/strip, P(confidence))} = \frac{\log(1 - \text{P(confidence)})}{\log(1 - \text{P(damage)})} \qquad (4)$$

Table 1: Prithvi requirements for aircraft runways.

CEP(m)	P(kill)	P(damage)	N(strip)	N(airbase)
50	0.2740	0.219	12	96
100	0.1650	0.132	21	168
150	0.1119	0.089	32	256
250	0.0580	0.046	64	512
300	0.0436	0.035	84	672

We will require that each strip be damaged with a probability of 0.95, i.e., P(confidence) = 0.95. While this may seem high, it should be noted, that since there are 8 such strips in each airbase (assuming that there are 4 such sections per airstrip and that there are 2 airstrips in each base), this requirement only leads to a probability of $(0.95)^8 = 0.66$ that all the strips in each airbase will be damaged. Thus, there is still more than a 1/3 chance that the airbase will have at least one operational strip that is sufficient for an airplane like the F-16 or a Mirage to take off. We multiply N(missiles/strip, P(confidence)) by 8 to obtain N(airbase), the number of missiles that have to be used for targeting a single airfield. The results are summarized in Table 1. Here and elsewhere, we round off numbers of missiles to the nearest integer.

It is clear that these numbers are very high and the targeting requirement for even one airbase exceeds India's current holdings, estimated at 60.[77] The military value of using fewer missiles than these to attack an air base, i.e., without ensuring a high probability of "crippling" the air base, is dubious; arguably, a surprise air attack would have greater effect. Targeting one air base alone will not ensure air superiority; that would require, at the very least, attacking all of the 17 air bases and airports. Given the estimated production rate of 3 a month,[78] this task is well beyond India's ability for quite some time.

COMMAND CENTERS AND BUNKERS

Each of the 10 military airbases is likely to contain one or more command centers, all of which should be targeted by Prithvi to ensure air superiority. Besides these, there may also be several other military command centers not necessarily associated with an airfield that would have to be targeted for a complete strike.

Table 2: Prithvi requirements for command centers.

CEP(m)	P(kill)	P(damage)	N(missiles)
50	0.105	0.084	16
100	0.0273	0.02184	63
150	0.0123	0.00984	140
250	0.0044	0.00352	393
300	0.0031	0.00248	558

For the purposes of calculation, we assume that a typical structure of this class is about 400 sq. m. in area and that at least 25 percent of the structure has to be damaged for it to cease operations. Assuming that the structure is 40 psi hard, this translates to the requirement that the warhead impact within a distance[79] of about 20 m from the center of the structure. Using Equation 3 we calculate P(kill) for the different CEP values. Multiplying this by 0.8 for the probability of launch, survival during flight and penetration of defenses, we obtain P(damage). To obtain the number of missiles required to ensure a 75 percent probability of damage to one target (i.e., P(confidence) = 0. 75), we substitute P(damage) into Equation 4 to calculate N(missiles). The results are compiled in Table 2.

The probability of kill decreases very roughly as the square of the CEP. Thus, the number of missiles needed to ensure a reasonable probability of damage increases dramatically with the CEP. Once again, except for the lowest CEP values considered, the targeting requirements for even one command center exceed the current stockpile of Prithvis. Assuming that only the centers associated with military air bases are targeted, there would be at least ten such centers that have to be attacked. This requirement, again, especially for higher values of the CEP, is well beyond India's capabilities, both at present and anywhere in the near future unless the production rate is increased dramatically.

A hardness value of 40 psi is likely to be an underestimate for hardened command centers. especially ones that may be underground. It is believed that at least some Pakistani command centers are built underground—for example, the Pakistan Air Defence Command Headquarters at Chaklala is reported to be built at a depth of somewhere between 5 and 10 meters.[80] Such a structure would presumably require over 100 psi for damage and would drive up missile requirements enormously.

RADARS

Pakistan possesses several radars as part of its air defense system. If a missile attack is to be used as a preamble to an air attack, it would make sense to target those. Pakistan's radars are believed to be of the following kinds: TRS-2215 and TRS-2230 (mobile and fixed/relocatable systems respectively, supplied by Thomson-CSF of France), AN/TPS-43 and AN/FPS-100 radars from Westinghouse of the USA, and Giraffe air defense radars from Ericsson of Sweden.[81] Some of the older systems include US-made FPS-89/100 and AR-1/15, Chinese Type-514, German Siemans MPDR 45/E, and Condor radars from the UK.[82]

Radar antennae are unlikely to function if subjected to overpressures of 5–10 psi. Unlike the case of runway destroying sub-munitions which require additional casing, we assume that radars are targeted by warheads with 100 sub-munitions per warhead, each with 10 kg of HE. This will result in overestimating the damage that a warhead is capable of.

To destroy a radar using cluster munitions, the warhead must land within a distance R_d (the dispersal radius) of the radar.[83] The probability of this is given by replacing X with R_d in Equation 2. Having landed within this distance, one of the sub-munitions must land within a distance R_L (lethal radius) of the radar/sub-munition combination. In accordance with our earlier assumption of the most optimal performance, we assume that 5 psi is sufficient for damaging a radar. The probability for this is:

$$P_D = 1 - \left(1 - \left(\frac{R_L}{R_d}\right)^2\right)^N \qquad (5)$$

The required probability, P(kill), for a warhead that survives launch and flight to damage a radar is given by the product of these two factors. Incorporating the factor 0.8 for the probability of launch survival during flight, and penetrating the defense, we obtain P(damage). Once again, requiring a 0.75 probability of damage, we substitute the value of P(damage) into Equation 4 to obtain N(missiles), the number of missiles needed for one target. In doing those calculations, we chose the value of R_d that maximized the probability. These results are summarized in Table 3.

While these numbers are much smaller, it must be remembered that many of those radars are mobile and in order to attack them successfully, their exact location must be known. This requires extensive intelligence gathering capabilities.

Table 3: Prithvi requirements for radars that are 5 psi hard.

CEP(m)	R_d	P(kill)	P(damage)	N(missiles)
50	90	0.7856	0.6285	2
100	125	0.4385	0.3508	3
150	155	0.2648	0.2118	6
250	195	0.1237	0.0989	13
300	220	0.0918	0.0735	18

Even without adding up all these separate requirements, it is clear that India lacks a sufficient number of Prithvis to mount a full-scale attack of the kinds of targets that have been mentioned in public reports.

AIRFORCE CAPABILITY

Many of the roles outlined here for Prithvi may also be performed by strike aircraft.[84] This fact is also recognized by the Indian air force, which has been undergoing modernization for several years aimed primarily at attacking Pakistan's air bases, air defense capabilities, and related infrastructure.[85] In the late 1980s, for example, the IAF purchased Armat anti-radar missiles from France and, in 1994, India acquired 315 Texas Instruments Paveway II guidance kits—used by the USA during the Gulf War to destroy Iraqi hardened aircraft shelters—for installation on British bombs.[86]

Apart from weapons designed specially for attacking runways, command centers and radars, the air force also has large numbers of aircraft and arms to take on the role of disabling Pakistani air bases. The total weapon load capacity of the 920 aircraft (with one sortie each) is equivalent to the capacity of about 3,000 Prithvi I or 6,000 Prithvi II. India's airforce capability[87] is summarized in Table 4. If we take into account the higher accuracy (i.e., lower CEPs) expected for air dropped bombs, especially the laser guided ones that India has been acquiring, they would be equivalent to many more missiles. Not included in this list are the long-range SU-30MK fighters, the first of which are expected to be delivered by Russia soon.

While the Indian Air Force will doubtless be challenged by Pakistan's air defense, most analysts believe that India still maintains superiority. It is worth noting that Pakistan does not have a large Surface-to-Air Missile (SAM) capability to shoot down high-flying planes.[88] Thus, the argument that mis-

Table 4: India's airforce capability.

Aircraft	Number	Max weapon load kg	Total weapon load kg	Combat radius km
MIG 21	360	1,145	412,200	390
MIG 23	140	4,500	630,000	600
MIG 27	170	5,000	850,000	750
MIG 29	96	3,500	336,000	650
Mirage 2000	45	6,300	283,500	750
Jaguar	109	4,550	496,000	680–1,000
Total	**920**		**3,007,700**	

siles cannot be defended against whereas airplanes can, though true in principle does not lead to the conclusion that missiles are always preferable; instead, the advantages and disadvantages of the two, with a consideration of the opponents defense capabilities, must be weighed. It is also worth noting that one study,[89] which compared ballistic missiles and strike aircraft, estimates the cost per ton of explosives delivered to be $1.25 million and $0.74 millions respectively.[90] Thus, delivering explosives by means of airplanes is clearly more economical.

EXPLANATIONS AND OPTIONS

Why Prithvi?

Given the limited military utility of Prithvi, unless deployed in vastly larger numbers than has ever been mentioned in reports, it is worth asking why Prithvi has not remained a "technology demonstrator"[91] and seems to be considered an operational system. There are several possible explanations.

While one might think that the Indian military wanted these missiles, there is some evidence to believe that at least some sections of the military were strongly opposed to this. One report says "the Army and Air Force had to be taken kicking and screaming to buy the Prithvi and even today the IAF (Indian Air Force) has shown no interest in an Agni-type missile or the means of delivering a nuclear retaliation against China."[92] Another article mentions how Prime Minister Rajiv Gandhi had to personally intervene to get the Army to accept Prithvis.[93] One reason for opposition may be the fear of spiraling costs; this would strike a chord with the Indian military which has been subject to shrinking budgets.[94] Apart from this, there is also some evidence that the army has considered the capabilities of Prithvi and found it wanting; for instance, one general is reported to have said "they have given us a glove that doesn't fit our hand."[95] Lastly, it has been suggested that the military seems "intent only on learning to fight the last war better;"[96] i.e., it is not interested in learning to use missiles but in continuing with bettering its air and tank war capabilities. Thus one possible explanation for the Prithvi program—that the military pushed for it—is clearly wanting.

A more plausible explanation is that Prithvi was purchased by the armed forces and made part of its war plans due to pressures from the DRDO. Unlike the space program, which enjoys wide support, DRDO's missile programs have had limited backing.[97] In addition, DRDO has been facing the problem of loss of skilled scientists and engineers to the more lucrative private sector, especially following the entry of multinational firms into the Indian market in the early 1990s. The slow progress of the Agni IRBM and Prithvi-II programs, as well as a solid propellant missile,[98] are indications of this. Further, and this is becoming increasingly true, each step in the missile program has been justified publicly by pointing to some dubious threat from Pakistan—the most recent example being the use of the reported test of Pakistan's Hatf missile to further the Agni program—or sometimes, even more dubious threats from missile possession by countries as far as Saudi Arabia. Such pressures from missile-development institutions are all too familiar from missile development programs in other states.[99]

Seen in this light, Prithvi is probably only a foot in the military door: judging from the experience of other countries, if the military has been persuaded to order and deploy Prithvis, it can be expected to call for higher numbers, higher ranges, higher payloads, greater accuracy and so on, thus creating a demand for DRDO products and expertise. This military pull becomes another factor in addition to the technological and institutional push from DRDO in mobilizing political support for the missile program. Given this, the enormous number of missiles required to carry out any significant military missions offer DRDO an opportunity to further affect military planning and resource allocation. Since a reduction in CEP by a factor of five or six can reduce the number of missiles required to destroy even one airfield from over 300 to less than fifty (Table 1), DRDO could demand that resources be concentrated on improving accuracy, i.e., on a DRDO mission, rather than on simply increasing the production of missiles. However, it should be noted that reducing the CEP to even tens of meters is no easy task.

It may well be that both the military, and especially the DRDO, realize that Prithvi is not militarily effective. Then the development of Prithvi must be viewed as just the first part of DRDO's ongoing missile efforts. Clearly Prithvi is the easiest to make since it is largely based on the Soviet SA-2 missile.[100] The introduction of Prithvi into India's arsenals is a visual demonstration of DRDO's mettle and would help garner public and institutional support for the Agni program and potential ICBM's in the future.

All this is not to say that there is no strategic value to be had from Prithvi. The value may be indirect. Pakistan is expected to respond by either producing and deploying indigenous Hatf missiles, or deploying the M-11s it is believed to have received from China. This would have several effects. First, Pakistan would be drawn into a costly arms race which it can little afford. Second, some Indian analysts hope that since deploying Chinese M-l Is could lead to US action against China, egging Pakistan on to divulging its possession of missiles from China would sour relationships between China, US and Pakistan.[101] This is a more attractive possibility for those in India who look at the increase in military cooperation between Pakistan and China, growing Chinese military and diplomatic strength, as well as China's friendship with the US suspiciously.

Military Options for Prithvi

If India does want to proceed with the Prithvi development and production program then the options for India to make Prithvis militarily more effective seem to be to increase the production rate and/or the accuracy of Prithvi, or use Prithvi with a nuclear warhead. As shown here, the production rate would have to increase massively for Prithvi to be militarily significant in the near future. This would be an expensive undertaking for the already cash-strapped Indian armed forces, or require diverting funds from other, more reliable and familiar, military programs. Increasing the accuracy of Prithvi may be possible, but there is no certainty that DRDO can deliver the necessary accuracy in the near future.

India could also change the targeting posture for Prithvi from attacking military targets to attacking civilian and military infrastructure, or using it as a terror weapon and attacking towns with military infrastructure in and around them as well as cities. As discussed earlier, the former is more likely in case of a protracted war, or in a punitive war, where at minimum risk India attempted to cripple Pakistan's military capability—similar to the way that the US attacked Iraq in the Gulf War. While use as a terror weapon is certainly possible it is worth remembering that the hundreds of rockets fired by

Germany against cities in England during the second world war failed to change the course of the war. A third alternative would be to use Prithvi against troop concentrations. However, India already possesses long range artillery that could be used for this role.

Options for Pakistan

In light of the above analysis, what options are available for Pakistan?

One immediate possibility is for Pakistan to deploy the Chinese made M-11 missiles it is said to have acquired. However, it is hard to imagine that the M-11 has a CEP much less than the values we have considered for Prithvi, and as such it is likely to be similar to Prithvi in its military effectiveness. Moreover, a far smaller proportion of corresponding key Indian targets would be within range of the M-11; by deploying them Pakistan would have only made the use of missiles be India more likely, and gained nothing. In fact, since it is likely that the Indian presumption will be the M-11s are armed with nuclear warheads, which are reportedly based on a Chinese design tested as a missile warhead in the 1960s, such deployment may be the response that will trigger the overt Indian nuclearization and deployment demanded by Indian hawks.

Another option is for Pakistan to invest in further development of its indigenous missiles. This is likely to be very expensive, time consuming, and uncertain in outcome given Pakistan's limited scientific and technological capabilities and the existing level of its missile program. And, as in the case of the M-11s, it is also unlikely to be militarily effective.

The most practical response, if any response is warranted other than a renewed commitment to a diplomatic solution to the relations between the two states, would be for Pakistan to invest in a variety of simple countermeasures. These would be relatively cheap and would make Prithvi attacks even more ineffective. Examples of such countermeasures include:

- hardening of military command posts, which would increase the requirements for Prithvi's accuracy tremendously;
- investing in metal sheets and quick setting concrete mixes for the air bases—these would allow planes to take off on even mildly damaged runways, and runways to be repaired within a matter of hours, respectively;
- investing in mobile radars—this would drive up the data collection requirements for India hugely.

Effectiveness of future Indian and Pakistani missiles

Our analysis also leads us to some conclusions about the effectiveness of Indian and Pakistani missiles that are said to be under development.

Indian Missiles

If Prithvi is not militarily effective with conventional weapons, Agni and other long range missiles are likely to be even less effective since they are likely to be even less accurate. Thus, they are not to be feared by either Pakistan, which in any case is more or less completely within the range of Prithvis, or China. Militarily, the only sense in which Agni can be used effectively is with nuclear warheads.

Pakistani Missiles

Like Prithvi, Pakistan's Hatf missiles are also not going to be militarily effective if used with conventional warheads. Since there are at least some indications that the Hatfs do not have a sophisticated guidance system,[102] it can at best be a terror weapon used against cities. In light of India's larger missile and air-strike capability, Pakistan would be ill-advised to attack in this manner.

CONCLUSIONS

The present capability of India's Prithvi missile, and the numbers that have been ordered to be incorporated into its armed forces, are such that they pose no significant immediate additional threat to Pakistan. At the present time they may be little more than an expression of institutional, political and strategic hopes and needs. However, these hopes and needs combined with an ill considered Pakistani response can drive a process that leads both countries into an expensive and ruinous arms race culminating in preparations for the use of nuclear armed missiles.

Postscript: Since this paper was written, both India and Pakistan have tested nuclear weapons. To date, there is no evidence suggesting these weapons have been deployed. It seems reasonable to presume that if India or Pakistan were to deploy missiles the other would presume them to be nuclear-armed and follow suit. It is therefore vital that there be an agreement to not deploy ballistic missiles. In exchange for no further tests of Ghauri, India should remove existing Prithvis to a distance greater than their range from the Indo-Pakistan border.

ACKNOWLEDGMENTS

We would like to thank Ted Postol, Frank von Hippel, Paul Podvig, David Wright, Lisbeth Gronlund, and George Lewis for comments and helpful suggestions.

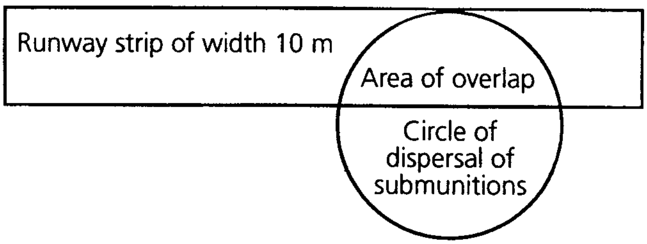
APPENDIX: DAMAGING AIRCRAFT RUNWAYS USING CLUSTER MUNITIONS

Each missile warhead carrying sub-munitions will spread them over a circle of radius R_d. Despite the potential difficulties in distributing the sub-munitions uniformly, we will assume a uniform distribution of sub-munitions. This is in line with other assumptions of optimal performance on the part of Prithvi. In order that no plane take off from the damaged runway, there needs to be no single stretch of runway available which is 400 m long and has a width of 10 m. B. Morel and T. Postol calculated the number of missiles required to ensure this by calculating the probable number of sub-munitions that would be deposited on a stretch of runway and assumed that if 20 or more sub-munitions are deposited, then the runway is destroyed. While this procedure is valid if the dispersal radius is relatively small, when R_d is large the geometric distribution of sub-munitions on the runways becomes an important factor. We will, therefore, use the following procedure.

The width of the runway required for frontline Pakistani aircraft to take off is less than 10 m (as mentioned earlier their wheel base is less than 5 m; thus 10 m allows for over a 100 percent margin of error). Thus, imagine the 50 m wide runway is divided into 5 strips, each of which is 10 m wide. Since the crater size for a 10 kg submunition designed for damaging runways is about 3 m in diameter, we will assume that each strip will require at least 3 sub-munitions to destroy it. For a given missile impact point with coordinates (x,y), the probability p that a particular submunition will hit this strip is the ratio between the area of overlap between the strip and a circle of radius R_d centered about (a,b), and the area of a circle of radius R_d, i.e.,

$$p(a,b) = \frac{\textit{area of overlap}}{\pi R_d^2}$$

We introduce the coordinates (a,b) into this equation to make the dependence of p on the missile impact point (more precisely, the relative positions of the strip and the missile impact point) explicit.



Then, the probability that at least three sub-munitions will hit the strip is:

$$P_3(p,N) = \left(1-(1-p)^N - Np(1-p)^{N-1} - \frac{N(N-1)}{2}p^2(1-p)^{N-2}\right) \quad (6)$$

Here N, is the number of sub-munitions. P_3 due to its dependence on p, depends on the position of the strip and where the missile lands.

Assuming the runway is a rectangle centered around the origin, we can compute the probability that for a missile landing at some point (x,y), each of the five strips of width 10 m is hit by three or more sub-munitions. Let us call this $q(x,y)$, this will be a complicated function of $P_3\ (p, N)$ that is to be evaluated for each of the five strips since they all have different areas of overlap with the circle of radius r_d about (x,y). The required probability that a strip of runway which has a width w and length l is damaged sufficiently so that planes cannot take off is given by:

$$P_{kill} = \frac{1}{2\pi\sigma^2}\iint_S q(x,y)\, e^{-(x^2+y^2)/(2\sigma^2)}\, dx dy \quad (7)$$

where S is the rectangle of length l and width $2^*(r_d - w/2)$ centered about the origin within which all missiles would have to land in order to damage the whole width of the runway;

$$\sigma = \frac{CEP}{\sqrt{2\ln(2)}}$$

P_{kill} depends on several variables—the CEP, the dispersal radius of submunitions the number of sub-munitions dispersed and the width w and length l needed for a plane to take off. Clearly the probability will increase with decreasing CEP, i.e., a more accurate missile, and increasing w and l. For any combination of inputs, there is an optimal dispersal radius. A very large dispersal radius will result in large areas within the circle of dispersal not being hit by any submunition. At the lower end, a dispersal diameter below the width of the runway, i.e., 50 m, will result in some section of the runway not being hit by any submunition. For values slightly greater than this, even if the radius of dispersal is greater than half the runway width, the warhead will have to land very close to the center of the runway for the sub-munitions to cover the entire runway. In view of the expected difficulties in dispersing submunitions, especially for smaller radii, we do not optimize this at a fine level, nor do we optimize it for each and every value of the CEP. For sub-munitions with the same explosive power, the probability increases with the number of sub-munitions carried by the warhead.[103] However, since the payload carried by a missile is fixed, as the number of submunitions increases, the explosive

Table 5: Variation of probability with inputs.

CEP(m)	R_d	n	l(m)	Probability
150	100	70	400	0.1119
100	100	70	400	0.1650
50	100	70	400	0.2740
250	100	70	400	0.0580
300	100	70	400	0.0436
150	100	70	300	0.1044
150	30	70	400	0.0608
150	150	70	400	0.0226
150	100	30	400	0.0004
150	100	100	400	0.2778

power goes down due to the addition of separate casings fuses, etc. Thus, for a given task, there is an optimum value. Once again, due to difficulties associated with dispersal, this may not be decided based on optimality conditions but on design considerations. We assume, therefore, that the warheads attacking runways use 70 sub-munitions per warhead. In order to appreciate better those variations, we present results for different combinations of these input values in Table 5. The first five rows represent the effects of changing CEP, with the first row being the "model case" The sixth row shows the effect of reducing the length required for take off. The seventh and eight rows show the effects of changing the dispersal radius and the last two rows show the effects of changing the number of sub-munitions (assuming that three of them are still required to damage each strip of width 10 m). The computations were performed on MatLab Version 5.0.

NOTES AND REFERENCES

1. Mian, Z. and A. H. Nayyar, "A Time of Testing?," *Bulletin of the Atomic Scientists*, (August/September 1996).

2. Smith, R. J., "India Moves Missiles Near Pakistani Border," *Washington Post*, (June 3. 1997).

3. Cooper, K. J., "India Denies It Has Deployed Missiles," *Washington Post*, (June 12, 1997).

4. "Pakistan to Counter Indian Missile Threat," *The News*, (June 5, 1997).

5. "Pakistan Missile Firing Triggers Indian Protest," *Aviation Week and Space Technology*, (July 21, 1997), p.35.

6. "India to Revive'Agni' Project," *The Hindu*, (July 31, 1997).

7. For details, see Wright, D.C., "An Analysis of the Pakistani Ghauri Missile Test of April 6, 1998," *Science and Global Security*, Vol. 7:2, pp. 227–234.

8. Morel, B. and T.A. Postol, "A Technical Assessment of Potential Threats to NATO from Non-Nuclear Soviet Tactical Ballistic Missiles, in New Technologies and the Arms Race," eds. C. Schaerf, B.H. Reid and D. Carlton, *St. Martins's Press*, (New York, 1989), pp. 106–160.

9. Karp, A., *Ballistic Missile Proliferation*, (Oxford University Press, 1996), p. 46.

10. Banerjie, I., "The Integrated Guided Missile Development Programme," *Indian Defence Review*, (July 1990), pp. 99–108.

11. Mannshaiya, H.K., "India's Prithvi—Government Held Hostage to its Missile," *International Defense Review*, Vol. 8, (1995), pp. 23–25.

12. Ramana, M.V. and D.C. Wright, "Modelling Prithvi and Agni," paper presented at the IX International Summer Symposium on Science and World Affairs, Cornell University, (July 24—August 3, 1997).

13. Inertial guidance uses only on-board instruments to guide the missile. A strap-down system is one that is not mounted on an inertial platform and thus undergoes the accelerations of the missile.

14. Joshi, M., "Missile Program on Hold," *Asia-Pacific Defence Reporter*, (April–May 1994).

15. The CEP, a measure of the accuracy of a missile, is the radius of an imaginary circle about the target point within which 50 percent of the missiles land.

16. Banerjie, *op. cit.*, (1990).

17. Sawhney, P., "Prithvi: Advantage India," *Hyderabad Deccan Chronicle*, (June 7, 1994), in JPRS-TND94–015.

18. Banerjie, *op. cit.*, (1990).

19. Gerardi, G.J., "India's 333rd Prithvi Missile Group," *Jane's Intelligence Review*, Vol. 7, no. 8, (1995), pp. 361–364.

20. Karp, *op. cit.*, (1996), p. 122.

21. Sawhney, P. "Prithvi's Position: India Defends Its Missile," *Jane's International Defense Review*, Vol. 7, (1997), pp. 43–45.

22. "Missile Program Intact," *Political Events*, (January 2, 1997).

23. See, for example, Mama, Hormuz, *Improved Prithvi Missile Launched; International Defense Review*, (August 1, 1992), p. 784. Banerjie, (1990), suggests that the fuel is UDMH with a Nitrous Oxide based oxidizer but this doesn't seem to be corroborated by anyone else.

24. Banerjie, *op. cit.*, (1990).

25. Chengappa, R., "Prithvi II—Boosting The Arsenal," *India Today*, (February 29, 1996), pp. 98–99.

26. Mama, *op. cit.*, (1992).

27. Lumpe, L., "A Flight Test Ban as a Tool for Curbing Missile Proliferation, in Peter Hayes (ed.)," *Rockets for Peace, Space Regimes, and ICBM Proliferation*, (Westview, 1996).

28. Gerardi, *op. cit.*, (1995).

29. *Ibid.*

30. "Missile Program Intact," *op. cit.*

31. Banerjie, *op. cit.*, (1990).

32. Sidhu, W.P.S., "Tactical Gap—Army Yet to Find a Role for the Weapon," *India Today*, (September 15, 1992).

33. Mannshaiya, *op. cit.*, (1995).

34. Gerardi, *op. cit.*, (1995).

35. Sawhney, P., "Prithvi and Pinaka will Change the Battlefield," *The Asian Age*, (April 13, 1995).

36. Gerardi, *op. cit.*, (1995).

37. Cherian, J., "The Missile Controversy," *Frontline*, (July 11, 1997), pp. 100–102.

38. Joshi, Manoj, "In the Shadow of Fear," *India Today*, (July 21, 1997), pp. 50–53.

39. Mannshaiya, *op. cit.*, (1995).

40. Sawhney, *op. cit.*, (1995).

41. *Ibid.*

42. Gerardi, *op. cit.*, (1995).

43. Ottenburg, M.A., "Operational Implications of Middle East Ballistic Missile Proliferation," *Defense Analysis*, Vol. 7, no. 1, pp. 3–19, (1991).

44. Mama, *op. cit.*, (1992).

45. Mannshaiya, *op. cit.*, (1995).

46. Gerardi, *op. cit.*, (1995). The use of a solid propellant means, of course, that it is a new missile, not a version of a liquid propellant missile.

47. Banerjie, *op. cit.*, (1990).

48. Banerjie, *op. cit.*, (1990); Sidhu, *op. cit.*, (1992).

49. Mannshaiya, *op. cit.*, (1995).

50. See, for example, Morel and Postol, (1989).

51. Banerjie, *op. cit.*, (1990).

52. "Prithvi Warhead Test Successful," *Rediff on The Net.*

53. The hardness of a target is usually characterized by the overpressure beyond which it is damaged.

54. Karp, *op. cit.*, (1996), pp. 102–103.

55. Morel and Postol, *op. cit.*, (1989).

56. Podvig, P., ed., *Russian Strategic Nuclear Weapons*, (IzdAT Publishers, Moscow, 1998). We are grateful to Paul Podvig for sharing this data with us.

57. See, for example, Altmann, J., "SDI for Europe?," *Technical Aspects of Anti-Tactical Ballistic Missile Defenses PRIF Research Report*, (1988); and Lewis, G.N. and T. A. Postol, "Video Evidence on the Effectiveness of Patriot During the 1991 Gulf War," *Science and Global Security*, Vol. 4, (1993), pp. 1–63.

58. Prithvi is also reported to be capable of maneuvering to avoid being shot down by ABM systems; since we are assuming that P(penetrating defense) = 1, this is not relevant to our analysis.

59. Assuming a Gaussian distribution of impact points, which is a safe assumption.

60. Kampani, G., "Prithvi: The Case for 'No-First Deployment'," *Rediff on the Net*, (July 11, 1997), http://www. redifindia.com/news/julueek2.htm.

61. For more precise formulae see, for example, Altmann, (1988), pp. 37–38.

62. Held, M., "Fragmentation Warheads: in Tactical Missile Warheads," ed. Joseph Carleone, American Institute of Aeronautics and Astronautics, Washington, (1993), pp. 387–464.

63. Kennedy, D.R., "Warheads: An Historical Perspective; in Tactical Missile Warheads," ed. Joseph Carleone, American Institute of Aeronautics and Astronautics, Washington, (1993), pp. 1–60.

64. Kennedy, *op. cit.*, (1993).

65. Altmann, *op. cit.*, (1988).

66. *SIPRI: Anti-personnel Weapons*, (Taylor and Francis, London, 1978), p. 173.

67. Morel and Postol, *op. cit.*, (1989).

68. Banerjie, *op. cit.*, (1990).

69. Sawhney, *op. cit.*, (1994); Sidhu, *op. cit.*, (1992).

70. Tellis, A.J., "Stability in South Asia," (RAND, 1997), p. 16.

71. Arnett, E., "Nuclear Stability and Arms Sales to India: Implications for U.S. Policy," *Arms Control Today*, (August 1997), p. 8.

72. Brzoska, M., and F.S. Pearson, *Arms and Warfare: Escalation, De-escalation, and Negotiation*, (University of South Carolina Press, 1994).

73. Morel and Postol, *op. cit.*, (1989), pp. 116–118.

74. Sidhu, *op. cit.*, (1992); Chaklala is a suburb of Rawalpindi.

75. These are ground-roll distances estimated from wing loading data from *Jane's All the World Aircraft 1996–97*, Surrey, UK, (1996), and using the methods outlined in Chapter 7 of McCormick, B.W., "Aerodynamics, Aeronautics and Flight Mechanics," (John Wiley and Sons 1995); Our estimates are more conservative than Morel and Postol, (1989).

76. The wheelbase of an F-16 is only 4 m and that of the Mirage is 4.87 m.

77. Joshi, *op. cit.*, (1997).

78. Gerardi, *op. cit.*, (1995).

79. A circular structure has been assumed for simplicity and because it has the minimum overlapping area with the damage radius.

80. Singh, P., R Rikhye and P. Steinemann, "Fiza'ya—Psyche of the Pakistan Air Force," *The Society for Aerospace Studies*, New Delhi, (1991).

81. *Jane's Land -Based Air Defence 1992–93*, Surrey.

82. Singh, Rikhye and Steinemann, *op. cit.*, (1991).

83. We are using the methodology outlined in Morel and Postol, (1989). However, since there appears to be a numerical error in one of their graphs, we calculated the requirements for radars using programs written on Matlab Version 5.0.

84. Harvey, J.R., "Regional Ballistic Missiles and Advanced Strike Aircraft—Comparing Military Effectiveness," *International Security*, (Fall 1992), Vol. 17, no. 2, pp. 41–83.

85. Arnett, E., "Conventional Arms Transfers and Nuclear Stability in South Asia," paper presented at the IX International Summer Symposium on Science and World Affairs, Cornell University, (July 24–August 3, 1997).

86. Arnett, *op. cit.*, *Arms Control Today*, (1997).

87. From SP's *Military Yearbook 1995*, and IIIS, *The Military Balance 96/97*, London, (1996).

88. Singh, Rikhye and Steinemann, *op. cit.*, (1991), pp. 100–102.

89. Center for International Security and Arms Control, Stanford University, "Assessing Ballistic Missile Proliferation and its Control," (November 1991).

90. This estimate assumes that a ballistic missile costs $1 million which is comparable to the cost of Prithvis estimated in the open literature which vary from $0.85 to $1.4 million.

91. A term used by India while describing tests of the Agni IRBM to indicate that it was not intended for deployment: this is also similar to the way India has described the 1974 nuclear test as a peaceful nuclear explosion.

92. Joshi, *op. cit.*, (1997).

93. Sawhney, *op. cit.*, (1994).

94. Pillai, A. and A. Bahal, "It's Time to Start Worrying," *Outlook*, (January 29, 1997).

95. Sidhu, *op. cit.*, (1992).

96. Joshi, *op. cit.*, (1997).

97. See, for example, Flank, S.M., "Reconstructing Rockets—the Politics of Developing Military Technology in Brazil, India, and Israel," MIT Thesis, (1993).

98. Sidhu, *op. cit.*, (1992), quotes the former director of DRDO, Dr. V. S. Arunachalam, as saying "We were looking for a thrust vector control and are using liquid engines, at least until our solid thrust vector control is ready." Given the Indian Space Research Organization's expertise with solid propellants, the delay in deploying a solid propellant version of the Prithvi only points to a lack of support or a severe lack of manpower.

99. See, for example, MacKenzie, D., "Inventing Accuracy," MIT, (1990).

100. Flank, *op. cit.*, (1993); Ramana & Wright, *op. cit.*, (1997).

101. "Missile Diplomacy," *India Today*, (August 31, 1995), p. 36.

102. A retired Pakistani military officer claims that "Pakistan's Half series are essentially rockets. Although there are some efforts to equip it with a guidance system;" see, Lt. Gen. (retd.) T. Masood, "Indian Missiles and the Peace Process," *Dawn*, http://www.dawn.com/daily/op/op.htm, (July 5, 1997).

103. Note that P_{kill} does not depend directly on the yield of the submunitions; the dependence is, however, built into our assumption that three submunitions would suffice to damage a 10 m wide section of the runway.