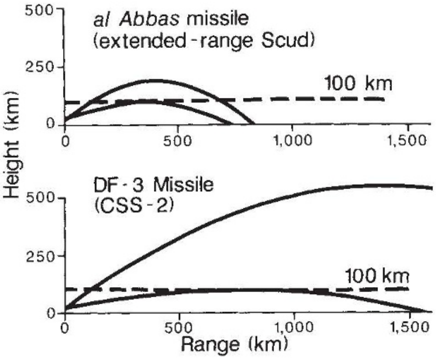
Underflying Brilliant Pebbles

SIR — Following the use of the Patriot missile in the Gulf War, the US Strategic Defense Initiative Office (SDIO) claims that its proposed space-based antimissile system Brilliant Pebbles could be used to destroy theatre ballistic missiles such as the extended-range Scud (the *al Abbas*), but its claim ignores a simple and effective countermeasure. SDIO has acknowledged that Brilliant Pebbles can intercept missiles only above about 100 km. Accordingly, if a missile's trajectory is adjusted so that it stays below this altitude throughout its flight, the missile becomes immune to Brilliant Pebbles. Our calculations show that flying theatre missiles on such depressed trajectories is not technically demanding; missiles with ranges considerably greater than those used by Iraq can underfly Brilliant Pebbles on trajectories with apogees of 100 km or less.



Minimum-energy maximum-range trajectories, and depressed trajectories with apogees of 100 km for the *al Abbas* and DF-3 missiles. The *al Abbas* has a maximum range of 830 km with a 250-kg warhead, and reaches an apogee of 190 km; on the depressed trajectory, it still has a range of 720 km. With a 2,000-kg payload, the DF-3 has a maximum range of 2,780 km with an apogee of 550 km; on the depressed trajectory, its range would be 1,550 km.

The Brilliant Pebbles altitude limit results from the high atmospheric densities at low altitudes; flying through regions of dense atmosphere at high speeds would blind the interceptors by heating their sensors. On 12 February 1991, SDIO director Henry Cooper stated that Brilliant Pebbles could not attack targets below roughly 60 miles (100 km). Lowering this altitude limit is difficult because of the exponential increase in atmospheric density with decreasing altitude. For example, in going from an altitude of 100 to 80 km, the density and resulting heating increase by a factor of 40.

To determine whether a missile could be flown on a depressed trajectory, we considered whether doing so would lead to unacceptable increases of stress ('loading') on the missile or heating on the re-entry vehicle and how it would affect the range and accuracy. We calculated the missile trajectories by numerically integrating the equations of motion[1], including forces due to gravity and atmospheric drag (lift was ignored). We compared the loading and heating for the depressed trajectory to that of the maximum-range minimum-energy trajectory for the same payload. The loading is roughly proportional to ρv^2, where ρ is the atmospheric density and v is the missile velocity; for the coefficient, we used measured values for the V2 missile[2]. The aerodynamic heating on re-entry is roughly proportional to ρv^3, and was calculated using equations for laminar and turbulent hypersonic flow (assuming a boundary layer transition at 30–35 km)[3].

To be specific, we considered two theatre-range missiles deployed in the Middle East: the 800-km Iraqi *al Abbas* and the Chinese-built 2,800-km DF-3 (CSS-2) missile deployed by Saudi Arabia. For the *al Abbas*, we assumed a total mass of 6,900 kg, fuel fraction of 80%, payload mass of 250 kg, specific impulse of 245 s, burntime of 115 s and booster diameter of 0.9 m (refs 4, 5 and S. Fetter, personal communication). For the DF-3, these parameters were taken to be 65,500 kg, 93.7%, 2,000 kg, 241 s, 142 s and 2.25 m (ref. 6). The weight-to-drag ratio for the DF-3 re-entry vehicle was taken as 48,000 N m^{-2}.

Calculations were done for depressed trajectories with apogees of 100 and 80 km. The loading was found to increase by 5–7% for the *al Abbas*, and 10–11% for the DF-3, which should be within the tolerances of both missiles. The heating was found to increase by 25–30% for the *al Abbas*, and 20–25% for the DF-3. This increase should not present a problem for the relatively crude *al Abbas*, for which the entire missile acts as the re-entry vehicle. If the increase in heat absorbed by the DF-3 RV exceeds its design tolerances, the heat shielding could be increased slightly, or the heating could be reduced to that of the standard trajectory by reducing the payload by 25%.

Flying missiles on depressed trajectories decreases their range; the percentage change increases with range (see figure). However, missiles with ranges of less than 1,500 km are sufficient to threaten most targets in the Middle East.

Our estimates suggest that the accuracy of these theatre ballistic missiles, which are very inaccurate, would not change significantly. Although errors due to atmospheric effects would increase on low-altitude trajectories, the dominant errors for these missiles are caused by the guidance system and would not be substantially affected. The inaccuracy of the *al Abbas*, estimated at 3–5 km (ref. 7), is not expected to change. The DF-3 inaccuracy of roughly 2.4 km (ref. 8) might increase by a factor of 2 to 3. As the original inaccuracy is so large that the only targets would be cities, such an increase would not remove its utility as a terror weapon.

Thus, theatre missiles like the *al Abbas* and DF-3 missiles would be able to fly on low-apogee depressed trajectories, thereby rendering them invulnerable to space-based defences.

DAVID C. WRIGHT
Federation of American Scientists,
307 Massachusetts Avenue, NE,
Washington DC 20002, USA
LISBETH GRONLUND
Center for International Security Studies,
University of Maryland,
7100 Baltimore Boulevard,
Suite 400, College Park,
Maryland 20740, USA

1. Regan F. J. *Reentry Vehicle Dynamics* 287 (American Institute of Aeronautics and Astronautics, New York, 1984).
2. Sutton, G. P. *Rocket Propulsion Elements* (3rd ed) 199 (Wiley, New York, 1965).
3. Anderson, J. D. *Hypersonic and High Temperature Gas Dynamics* 288–291 (McGraw-Hill, New York, 1989).
4. Zaloga, S. *International Defense Review* **21**, 1423 (1988).
5. Cochran, T. B., Arkin, W. A., Norris, R. S. & Sands, J. I. *Soviet Nuclear Weapons* 220, (Ballinger, Harper and Row, Cambridge, Massachusetts, 1989).
6. Huang, Z. & Ren, X. *Space Technology* **8**, 371 (1988).
7. *Jane's Defence Weekly* **15**, 103 (1991).
8. Shuey, R. D. *et al. Missile Proliferation: Survey of Emerging Missile Forces* 65 (Congressional Research Service, Washington, 1988).

Is C_{60} stiffer than diamond?

SIR — The availability of single crystals of C_{60} (ref. 1) should allow measurements of the stiffness of these molecules. By using a simple elasticity argument, we estimate the bulk modulus of individual C_{60} molecules to be 843 GPa, which is greater than that of diamond (441 GPa). We expect that the modulus of single crystals of C_{60} will reach 642 GPa at modest pressures and that crystalline C_{60} will then be stiffer than diamond at the same pressure.

Consider a single crystal of graphite with equal orthogonal tensile (or compressive) stress components applied to areas normal to the basal plane. Let x_3 be the direction along the c axis and x_1 and x_2 lie in the basal plane. The stress state is

$$\begin{bmatrix}\sigma_1 & & \\ & \sigma_2 & \\ & & 0\end{bmatrix} = \begin{bmatrix}\sigma & & \\ & \sigma & \\ & & 0\end{bmatrix}$$

Hence the longitudinal strains ε_1 and ε_2 are given by

$$\varepsilon_1 = \varepsilon_2 = S_{11}\sigma_1 + S_{12}\sigma_2 = (S_{11}+S_{12})\sigma$$

where the S_{ij} are elastic compliances. The dilation ΔA of the basal area A is

$$\frac{\Delta A}{A} = \varepsilon_1 + \varepsilon_2 = 2(S_{11} + S_{12})\sigma$$

If h is the height of a graphite basal plane (one half of the lattice spacing c because of the ABAB stacking sequence) then

$$\frac{\Delta A}{A}h = 2(S_{11}+S_{12})\sigma h = 2(S_{11}+S_{12})\gamma \qquad (1)$$