METEORITE IMPACTS AND THE COMPREHENSIVE TEST BAN TREATY. C. F. Chyba[1], G. E. van der Vink[2] and C. B. Hennet[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721 USA, chyba@lpl.arizona.edu, [2]IRIS Consortium, 1200 New York Ave., SW, Suite 800, Washington DC 20005, USA.

In September 1996, President Clinton signed the Comprehensive Test Ban Treaty (CTBT) at the United Nations. Testing of nuclear weapons in the atmosphere, in outer space, or underwater had previously been banned by the Partial Test Ban Treaty, signed by President Kennedy in 1963. The CTBT extends this ban to include underground tests, limiting further development of nuclear weapons by those nations already possessing them, and impeding the proliferation of nuclear weapons among those nations that do not.

Crucial to the CTBT are verification measures to minimize the chances of the treaty being violated. In particular, the CTBT calls for an International Monitoring System (IMS) consisting of a number of components. These include a primary and auxiliary seismic network, a radionuclide monitoring network, a hydroacoustic network, an infrasound network, and on-site inspections.

The primary network of the IMS will consist of 50 stations, transmitting data continuously in near real-time to an International Data Center where they will be used for event detection. The auxiliary network of the IMS will consist of some 120 stations used to refine the parameters (such as location, depth, and magnitude, with the latter translating in the case of an underground explosion into the explosive yield of the nuclear device) of an event detected by the primary network[1].

The Director of the U.S. Arms Control and Disarmament Agency stated in 1996 that the seismic network would have a detection capability "significantly below a seismic magnitude of four, or roughly one kiloton fully-coupled in hard rock. For many places on the globe, the event detection threshold for the prototype system is routinely about seismic magnitude three . . . ."[2] For the range of magnitudes that could be of interest for treaty monitoring, we determine how often meteorites of the corresponding impact energy will strike the Earth. Seismic detections of such impacts could cause concern if they were difficult to distinguish from explosions (the recent event over Greenland may help to answer this question) and were associated with potential terrorist activity or illicit weapons development.

A seismic event in Western Australia in 1993 provides an illustration. In May of that month, a seismic event of magnitude 3.6 was registered, the epicenter of which was just south of Banjawarn Station, where members of the Aum Shinrikyo terrorist cult had been trying to mine uranium, and carrying out tests with chemical weapons. Suspicion arose that the seismic event was somehow related to activities of the cult. For the Senate Select Committee on Investigations, we looked at a variety of possible explanations for this event, including an earthquake, an explosion, and a meteorite impact. We concluded that the most likely explanation was the impact of an iron meteorite with a radius upon entering the Earth's atmosphere of nearly 2 meters. The resulting explosion should have excavated a crater a bit over 100 m in diameter[3].

The purpose of the work described here is to look at the question more generally: how often will hypervelocity meteorite impacts be detected by the IMS for seismic magnitudes in the range of monitoring interest?

Teleseismic body wave magnitude M is known as a function of explosive yield Y for underground nuclear explosions over a broad range of yields and source media. The data are well fit by a linear relationship between M and log(Y), though this equation must be adjusted for the seismic characteristics of particular geographical regions. For example, for sites with low seismic attenuation, such as the former Soviet test sites near Semipaltinsk and on Novaya Zemlya, the M-Y relationship[4] is $M = 4.45 + 0.75 \log(Y)$, where Y is in kilotons. For an area of high seismic attenuation, such as the Nevada Test Site in the U.S., the relationship is instead[5] $M = 3.92 + 0.81 \log(Y)$. These equations bracket the range of appropriate relationships around the world.

To apply these equations to impacts, we have to make allowance for different coupling efficiencies of yield energy into seismic waves for nuclear explosions and impacts. Underground nuclear explosions in the energy range from 1 to 19 kt have a typical coupling efficiency[6] of about 0.005. The coupling efficiency for impacts is smaller. For the iron meteorites whose impacts will prove of interest here, coupling efficiency is about 0.0001, based on a variety of results[7]. This is also about that appropriate for large asteroid impacts into crustal rock[8]. Clearly these numbers are approximate, and must in fact vary with target.

For meteorite impact kinetic energy E, the M-E reltionship is then similar to that for M-Y, but with E divided by the ratio of coupling efficiencies. For example, for low attenuation sites, we have $M = 4.45 + 0.75 \log (E/50)$, and analogously for regions of high attenuation. By these equations, a seismic event of magnitude 4 corresponds to a nuclear yield Y in the range 0.25 to 1.25 kt, but to an impactor with impact kinetic energy in the range 12.5 to 62.5 kt. A magnitude 2.5 event requires an impactor with kinetic energy in the range 0.1 to 0.9 kt.

How often is Earth struck by meteorites with energies in the range from 0.1 kt to 100 kt? Data for the cumulative impact frequency F vs. kinetic energy (at the top of the atmosphere!) G for small Earth-crossing asteroids (ref. 8) are well fit by the equation F = 12.6 G ^ -0.86, where F is in 1/yr and E is in kt. However, the filtering effect of the terrestrial atmosphere must be taken into account. For example, Earth's atmosphere filters out non-iron meteors entering the atmosphere with energies below about 2 Mt; these weaker objects typically explode in the atmosphere instead[9].

Iron objects entering the atmosphere will be ablated and decelerated, so that a small object entering the atmosphere with energy G will strike the surface with substantially less impact energy E. To include this effect, we employ a numerical simulation of the ablation, deceleration, and catastrophic disruption of small asteroids entering Earth's atmosphere that worked well for modeling the Tunguska and Revelstoke meteorite explosions[10]. We adopt the parameters for iron meteorites used in that study, incorporating modifications in drag coefficient, shock layer temperature, and heat-transfer rate suggested by Lyne and Tauber[11].

Finally, we take into account a variety of data that suggest that iron objects comprise only about 5% of the small impactors striking Earth [7] , and that 70% of Earth's surface area is water. The uncertainty in the former estimate is perhaps a factor of two.

We find (ref. 7) that for seismic magnitude detection thresholds around 3, hypervelocity impacts of meter-scale iron meteorites will occur on a timescale of decades. Magnitude 4 events will occur on century timescales. Given the many uncertainties in these calculations, especially those due to local geology and coupling efficiencies, it is doubtful that conclusions about event frequencies more precise than these order-of-magnitude statements can be reliably made. Although there are no known broadband digital seismic recordings of meteorite impacts, this suggests that the current seismological data archives include meteorite impacts that have been mistakenly categorized as earthquakes.

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