Earth Impact Effects Program: A Web-based Computer Program for Calculating the Regional Environmental Consequences of a Meteoroid Impact on Earth

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Abstract. We have developed a web-based program for quickly estimating the regional environmental consequences of a comet or asteroid impact on Earth. This paper details the observations, assumptions and equations upon which the program is based. It describes our approach to quantifying the important impact processes that might affect the people, buildings and landscape in the vicinity of an impact event and discusses the uncertainty in our predictions. The processes included are: Atmospheric entry, impact crater formation, fireball expansion and thermal radiation, ejecta deposition, seismic shaking and the propagation of the blast wave.

1. Motivation

Asteroid and comet impacts have played a major role in the geological and biological history of the Earth. It is widely accepted that one such event, 65 million years ago, perturbed the global environment so catastrophically that a major biological extinction ensued. As a result, both the scientific community and the general populace are increasingly interested in both the threat to civilization, and the potential environmental consequences of impacts.

At present, there exists no single reference source for estimates of the environmental effects of an impact event; for example, ejecta thickness, blast wave pressure, ensuing wind velocities. Moreover, there is no reasonable way for the mainstream media or general public to access this information. To fill a much needed niche in impact cratering resources, we have developed a user-friendly, web-based program for estimating the environmental consequences of a given impact, at a certain distance away. We have developed the site to be used by both scientists and the general public alike.

The web page, which is located at:

www.lpl.arizona.edu/ImpactEffects,

asks users to supply their desired distance away from the impact r, the size of the meteoroid L (NB: the terms "meteoroid," which encompasses both asteroid and comets, and "impactor" are used interchangeably in this document), the impact velocity v_i, the angle of impact measured from the horizontal plane at the surface of the Earth θ and the density of the impactor (meteoroid) ρ_i and target ρ_t. The current program includes estimates of crater size, seismic effects, ejecta thickness, airblast pressures and the intensity of thermal radiation.

2. Impact energy and recurrence interval

The most important variable for quantifying the environmental consequences of an impact event is the kinetic energy E of the meteoroid at the moment of impact; that is, one half times the impactor mass m_i times the square of the impact velocity v_i, which can be rewritten in terms of the meteoroid's density ρ_i and diameter L, assuming that the meteoroid is approximately spherical:

$$E = \frac{1}{2} m_i v_i^2 = \frac{\pi}{12} \rho_i L^3 v_i^2. \qquad (1)$$

Objects that encounter the Earth are either asteroids or comets. Asteroids are made of rock ($\rho_i \sim 2500 - 3000$kg m^3) or iron ($\rho_i \sim 8000$kg m^3) and typically collide with the Earth's atmosphere at velocities of 15-20 km s^{-1}. Detailed knowledge of the composition of comets is currently lacking; however, they are of much lower density ($\rho_i \sim 500 - 1500$kg m^3) and composed mainly of ice. Typical velocities at which comets encounter the Earth's atmosphere are in the range of 30-70 km s^{-1}.

Observations of Near-Earth Objects made by several telescopic search programs show that the number of near-Earth asteroids with a diameter greater than L (in km) may be expressed approximately by the power law[Near-Earth Object Science Definition Team, 2003]:

$$N(> L) = 1148 L^{-2.354}. \qquad (2)$$

These data may also be expressed in terms of the recurrence interval T_{RE} in years versus impact energy E_{MT} in MegaTons. This allows us to inform the user of the average time between impacts of the specified energy (in MT) somewhere on the Earth. The equation we use is:

$$T_{RE} = 110 E^{0.77}. \qquad (3)$$

Furthermore, we can estimate the recurrence interval T_{RL} for impacts of the same energy within a region of the Earth's surface with a radius equal to the user-specified distance r. This is simply the product of the recurrence interval for the whole Earth and the fraction of the Earth's surface area that is within the distance r:

$$T_{RL} = T_{RE} \frac{1 - \cos(r/R_E)}{2}. \qquad (4)$$

The relative importance of comets to the Earth-crossing impactor flux is not currently well constrained. The Near-Earth Object Science Definition Team [2003] suggest that comets comprise only about 1% of the estimated population of small NEOs; however, there is evidence to suggest that at larger sizes comets may comprise a significantly larger proportion of the impactor flux. Of the asteroids that collide with the Earth's atmosphere the current best estimate is that approximately 5% are iron asteroids [Bland and Artemieva, 2003].

3. Atmospheric Entry

The velocity that the meteoroid possesses at the moment of impact, after traversing through the atmosphere, is a function of its size. The mass of atmospheric gas along the incoming trajectory of a meteoroid m_a is given by [Melosh, 1989, p. 205]:

$$m_a = \frac{P_0}{g_0 \sin\theta} A_i, \qquad (5)$$

where P_0 is the ambient pressure at the surface of the Earth (1 bar = 10^5 Pa), g_0 is the gravitational acceleration at the surface of the Earth (9.8 ms^{-1}), θ is the angle of the trajectory to the surface and A_i is the cross-sectional area of the impactor. Momentum conservation tells us that the velocity of the impactor after traversing through the atmosphere is:

$$v_i = \frac{m_i}{m_i + m_a} v_\infty = \frac{\rho_i L}{\rho_i L + \frac{3P_0}{2 g_0 \sin\theta}} v_\infty, \qquad (6)$$

where ρ_i is the impactor density and L is the impactor diameter. Examination of equation 6 shows that for large impactor diameters the effect of the atmosphere can be neglected; however, small impactor's are slowed considerably by the atmosphere. We assume that an impacting meteoroid is essentially "stopped" by the atmosphere if its final velocity is less than 10% of its original value. In this case, the critical diameter above which all impactor's will produce an impact crater is given by:

$$L_{crit} = 0.15 \frac{P_0}{\rho_i g_0 \sin\theta}. \qquad (7)$$

We use this criterion to check that the user defined impact parameters will produce an impact crater. If the impactor diameter is greater than L_{crit} the program continues; if the impactor diameter is less than this value the program reports that no crater is formed.

4. Crater Size

Determining the size of the final crater from the user-specified impactor size, velocity and angle of incidence is not an easy task. The formation of an impact crater is an extremely complicated and dynamic process. The abrupt deceleration of a comet or asteroid as it collides with the Earth transfers an immense amount of kinetic energy from the impacting body to the target. As a consequence, the target and impactor are rapidly compressed to very high pressures and heated to enormous temperatures. Between the compressed and uncompressed material a shock wave is created that propagates away from the point of impact. In the wake of the expanding shock wave the target is comprehensively fractured, shock-heated, shaken and set in motion—leading to the excavation of a cavity many times larger than the impactor itself. This temporary cavity (often termed the transient crater) subsequently collapses under the influence of gravity to produce the final crater form.

The central difficulty in deriving an accurate estimate of the final crater diameter is that there are no observational or experimental data for impact craters larger than a few tens of meters in diameter. Perhaps the best approach is to use sophisticated numerical models capable of simulating the propagation of shock waves, the excavation of the transient crater and its subsequent collapse; however, this method is beyond the scope of a simple web-based tool. Instead, we use a set of scaling laws that extrapolate the results of small-scale experimental data to scales of interest. The first scaling law we apply was derived by Schmidt and Housen [1987] based on a wide range of experimental cratering data (for example, small-scale hypervelocity experiments and nuclear explosion experiments). This equation relates the density of the target ρ_t and impactor ρ_i, the impactor diameter L, the impact velocity v_i and the Earth's surface gravity g_E to the diameter of the transient crater D_{tr} as measured at the pre-impact target surface:

$$D_{tr} = 1.161 \left(\frac{\rho_i}{\rho_t}\right)^{1/3} L^{0.78} v_i^{0.44} g_E^{-0.22} \qquad (8)$$

This equation applies for impact events where gravity is the predominant arresting influence in crater growth, which is the case for all terrestrial impacts larger than a couple of hundred meters in diameter. The equation is also for vertical impacts only. The effect of obliquity is currently poorly known. We adopt a simple way of including its effect outlined by Chapman and McKinnon [1986], whereby the impact velocity v_i is replaced by the vertical component $v_i \sin\theta$, where θ is the angle of impact measured from the plane of the target.

The transient crater diameter is only an intermediate step in the development of the final crater. To estimate the final crater diameter we must consider the effect of the transient crater's collapse using another scaling law. For small craters (classified as "simple" based on their intuitive morphology; less than $\sim$ 3.2 km on Earth) the collapse process is well-understood. It is observed that in this case the transient crater grows by a constant proportion during collapse, regardless of diameter. Thus, for simple craters we assume that the final crater rim-to-rim diameter D_f is given by:

$$D_f = 1.56 D_{tr}. \qquad (9)$$

For craters larger than 3.2 km on Earth (termed complex because of their unintuitive morphology) the collapse process is poorly understood and involves the complicated competition between gravitational forces tending to close the transient crater and the strength properties of the post-impact target rocks. Several scaling laws exist for estimating the final crater diameter from the transient crater diameter of a complex crater, or vice versa, based on reconstruction of the transient craters of lunar complex craters [see for example, Croft, 1985;

McKinnon and Schenk, 1985; Holsapple, 1993]. We use the functional form:

$$D_f = \frac{1.17 D_{tr}^{1.13}}{D_c^{0.13}}, \quad (10)$$

derived by McKinnon and Schenk [1985], which lies intermediate between the estimates of Croft [1985] and Holsapple [1993]. In this equation D_c is the diameter at which the transition from simple to complex crater occurs (taken to be 3.2 km on Earth).

5. Thermal Radiation

The immense amount of kinetic energy possessed by the impactor is transferred to the target in the blink of an eye. The resulting compression of the target drastically raises the temperature and pressure of a small region proximal to the impact site, melting and vaporizing the entire projectile and some target material. The vapor produced is initially at very high pressure (>100 GPa) and temperature (>10,000 K) and thus begins to rapidly expand; it is termed the "fireball." The high temperatures imply that the emission of thermal radiation is an important part of the energy balance of the expanding plume. Initially the fireball is so hot that the air is ionized and its radiation absorption properties are substantially increased. As a result the fireball is initially opaque to the emitted radiation, which can therefore not escape. With continued expansion, the fireball cools until the temperature falls below a critical temperature, known as the transparency temperature T_* [Zel'dovich and Raizer, 1966, p. 607]. At this time the opacity rapidly diminishes and the fireball is unveiled, bathing the Earth's surface in thermal radiation. For Earth's atmosphere the transparency temperature is $\sim 3000°$K, hence the thermal radiation is primarily in the visible and infrared wavelengths—the fireball appears as a "second sun" in the sky.

To provide a measure of the fireball's dimension, we determine the fireball radius R_{f*} at the moment the transparency temperature is achieved, which defines the time of maximum radiation. Numerical simulations of vapor plume expansion [Melosh *et al.*, 1993] predict that the fireball radius at the time of maximum radiation is 10-15 times the impactor radius. We use a value of 13 and assume "yield scaling" applies to derive a relationship between impact energy E in joules and the fireball radius in meters:

$$R_{f*} = 0.027 E^{1/3}. \quad (11)$$

Yield scaling is the empirically-derived concept that certain length- and time-scales measured for two different explosions (or impacts) are approximately identical if divided by the cube root of the yield (or impact) energy. Yield scaling can be justified theoretically, provided that gravity and rate dependent processes do not strongly influence the measured parameters [Melosh, 1989, p. 115].

To calculate the time at which thermal radiation is at a maximum, we assume that the expansion of the fireball occurs at approximately the same velocity as the impact. This time is, therefore, simply the fireball radius divided by the impact velocity:

$$T_t = \frac{R_{f*}}{v_i}. \quad (12)$$

To give a sense of the brilliance of the fireball we compare the angular width of the fireball at the specified distance (given approximately by R_{f*}/r) with the angular width of the Sun ($\sim 8.7 \times 10^{-3}$ radians). The program reports that the fireball appears B times larger than the Sun, where B is given by:

$$B = \frac{R_{f*}}{8.7 \times 10^{-3} r}. \quad (13)$$

The total amount of thermal energy emitted as thermal radiation is some small fraction η (known as the "luminous efficiency") of the impact energy E. The luminous efficiency for hypervelocity impacts is not presently well constrained. Numerical modeling results [Nemtchinov *et al.*, 1998] suggest that η scales as some power law of impact velocity. The limited experimental and numerical results that exist indicate that for typical asteroidal impacts with Earth, η is in the range of $1-5\times10^{-4}$; we assume $\eta = 3 \times 10^{-4}$ and ignore any velocity dependence.

To quantify the amount of heating at a specified distance away from the impact, we next determine the thermal exposure Φ, which is given by the total amount of thermal energy radiated ηE divided by the area over which this energy is spread (the surface area of a hemisphere of radius equal to the specified distance, $2\pi r^2$):

$$\Phi = \frac{\eta E}{2\pi r^2}. \tag{14}$$

The total thermal energy per unit area Φ that heats our location of interest arrives over a finite time period between the moment the fireball surface cools to the transparency temperature and is unveiled, to the moment when the fireball has expanded and cooled to the point where radiation ceases. We define this time period as the "duration of irradiation" τ_t. Without computing the hydrodynamic expansion of the vapor plume this duration may be estimated simply by dividing the total energy radiated per unit area (total thermal energy emitted per unit area of the fireball) by the radiant energy flux, given by σT_*^4, where $\sigma = 5.67\times10^{-8}$W m^{-2} K^{-4} is the Stefan-Bolzmann constant. The duration of irradiation is then:

$$\tau_t = \frac{\eta E}{2\pi R_{f*}^2 \sigma T_*^4}. \tag{15}$$

For situations where the specified distance away from the impact point is so far that the curvature of the Earth implies that part of the fireball is below the horizon, we modify the thermal exposure Φ and solar-relative size B by multiplying by the ratio f of the area of the fireball above the horizon to the total area. This is given by:

$$f = \frac{2}{\pi}\left(\delta - \frac{h}{R_{f*}}\sin\delta\right). \tag{16}$$

In this equation, h is the maximum height of the fireball below the horizon as viewed from the point of interest, given by:

$$h = (1 - \cos\Delta)R_E, \tag{17}$$

where Δ is the epicentral angle between the impact point and the point of interest and R_E is the radius of the Earth. If $h \geq R_{f*}$ then the fireball is entirely below the horizon; in this case the program reports that "no direct thermal radiation reaches the point of interest."

The angle δ in Equation 16 is half the angle of the segment of the fireball visible above the horizon, given by $\delta = \cos^{-1} h/R_{f*}$.

Whether a material catches fire as a result of the fireball heating depends not only upon the corrected thermal exposure $f\Phi$ but also on the duration of irradiation. This is because for a longer duration of heating there is sufficient time for some heat to be conducted through the material, thus reducing the surface temperature. We account for this effect by defining an ignition exposure ξ, which is the thermal exposure divided by the total thermal radiation (in MegaTons) to the one-sixth power:

$$\xi = \frac{f\Phi}{(\eta E_{MT})^{1/6}}. \tag{18}$$

This ignition exposure is compared with values for the exposure required to ignite various materials in a 1 MT explosion (see Table 1) and the results are reported to the user.

6. Seismic Effects

The shock wave generated by the impact expands and weakens as it propagates through the target. Eventually, all that remains are elastic (seismic) waves that travel through the ground and along the surface in the same way as those excited by earthquakes, although the structure of the seismic waves induced by these different sources is likely to be considerably different.

To calculate the seismic magnitude of an impact event we assume that the fraction of the kinetic energy of the impact that ends up as seismic wave energy is one part in ten thousand (1×10^{-4}). This

Table 1. Ignition Exposure

Ignition Exposure, J m^{-2}	Description
10^6	Clothing ignites
6.7×10^5	Plywood flames
4.2×10^5	Much of the body suffers third degree burns
3.8×10^5	Grass ignites
3.3×10^5	Newspaper ignites
2.5×10^5	Much of the body suffers second degree burns
2.5×10^5	Deciduous trees ignite
1.3×10^5	Much of the body suffers first degree burns

Data Extracted from Glasstone and Dolan [1977]

value is the most commonly accepted figure based on experimental data [Schultz and Gault, 1975], with a range between 10^{-5}–10^{-3}. Using the classic Gutenberg-Richter magnitude energy relation, the seismic magnitude M is then:

$$M = 0.67 \log_{10} E - 5.87, \tag{19}$$

where E is the initial kinetic energy of the impactor in Joules [Melosh, 1989, p. 67]. The program reports this magnitude.

To estimate the extent of devastation at a given distance from a seismic event of this magnitude we must determine the intensity of shaking I, as defined by the Mercali scale. We achieve this by calculating an "Effective seismic magnitude," which we define as the magnitude of an earthquake centered at the user-specified distance that produces the same ground motion amplitude as is produced by the impact-induced seismic shaking centered at the impact site. We then use Table 2 to relate the effective seismic magnitude to the Mercali Intensity. A range of intensities is associated with a given seismic magnitude because the severity of shaking will depend on the behavior of the ground; for example, damage in alluviated areas will be much more severe than on well-consolidated bed rock.

Table 2. Seismic Magnitude/Intensity Relationship

Magnitude	Intensity
0	-
1	I
2	I-II
3	III-IV
4	IV-V
5	VI-VII
6	VII-VIII
7	IX-X
8	X-XI

The equations for effective magnitude use curves fit to empirical data of ground motion as a function of distance from earthquake events in California [Richter, 1958, p.342]. We use three functional forms to relate the effective seismic magnitude $M_{\rm eff}$ to the actual seismic magnitude M and the distance from the impact site r (in km), depending on the distance away from the impact site. For $r < 70$ km:

$$M_{\rm eff} = M - 0.0238r + 0.0658; \tag{20}$$

for $70 \leq r < 750$ km:

$$M_{\rm eff} = M - 0.0048r - 1.1644; \tag{21}$$

and for $r \geq 750$ km:

$$M_{\rm eff} = M - 1.66 \log_{10}(r/R_E) - 6.399. \tag{22}$$

Once the Mercali Intensity is defined, the program outputs the associated description (see Table 3).

Many assumptions are included in this procedure that introduce substantial uncertainty in the prediction of ground shaking intensity. The data used for the curves of ground motion amplitude as a function of distance are limited in number and geographical location. Hence, the important effects of ground rheology are not included in this simple calculation. We further assume that the main seismic wave energy is that associated with the surface waves. The seismic arrival time, therefore, is computed by simply dividing the user-specified distance by the typical speed of sound of upper-crustal rocks (5 km s^{-1}).

7. Ejecta

To estimate the thickness of ejecta at a given distance from the impact, we assume that the ejecta layer has a maximum thickness at the crater rim and falls off as one over the distance from the crater rim cubed.

$$t_e = \frac{t_{rim}}{8}\left(\frac{D_{tr}}{r}\right)^3 \tag{23}$$

The power of -3 is a good approximation of data from explosion experiments [McGetchin *et al.*, 1973] and a satisfactory compromise for results from numerical calculations of impacts and shallow-buried nuclear explosions, which show that the power can vary between -2.5 and -3.5. To calculatd the ejecta thickness at the rim t_{rim} we use a simple volume conservation argument: we equate the volume of the ejecta deposit, given by:

$$V_e = \frac{t_{rim}D_{tr}^3}{8}\int_{D/2}^{\infty}\frac{2\pi r dr}{r^3} = \frac{\pi t_{rim}D_{tr}^2}{2}, \tag{24}$$

with the volume of the transient crater, which for a paraboloid of revolution with a depth to diameter ratio of 1:3 is given by:

$$V_{tr} = \frac{\pi D_{tr}^3}{24}. \tag{25}$$

This gives:

$$t_{rim} = \frac{D_{tr}}{12}, \tag{26}$$

which is a reasonable approximation of measurements of rim height and rim diameters for simple craters on the Moon [Pike, 1977]. Inserting this equation for rim height into Equation 23 gives:

$$t_e = \frac{D_{tr}^4}{96r^3}. \tag{27}$$

As this derivation ignores the bulking of the ejecta deposit and the entrainment of the substrate on which the ejecta lands it provides a lower-bound on the probable ejecta thickness. The use of transient crater diameter, instead of final crater diameter avoids the need for a separate rim height equation for simple and complex craters. Rim heights of complex craters, as a fraction of the final crater diameter, are significantly smaller than the scaled rim heights of simple craters because for complex craters the thickest part of the ejecta blanket collapses back into the final crater during the late stages of the cratering process. As this collapse process is not fully understood, we only report the ejecta thickness outside the final crater rim.

Table 3. Mercali Intensity Scale

Intensity	Description
I	Not felt. Marginal and long-period effects of large earthquakes.
II	Felt by persons at rest, on upper floors, or favorably placed.
III	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. May not be recognized as an earthquake.
IV	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.
V	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).
VII	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
VIII	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse;masonry B seriously damaged. (General damage to foundations) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.
X	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	As X. Rails bent greatly. Underground pipelines completely out of service.
XII	As X. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A: Good workmanship, mortar, and design; reinforced, especially laterally, and bound together using steel, concrete, etc.; designed to resist lateral forces.

Masonry B: Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C: Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D: Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

The ejecta arrival time is determined using ballistic travel time equations derived by Ahrens and O'Keefe [1978] for a spherical planet assuming all ejection is at a 45° angle to the planet's surface. The travel time T_e is:

$$T_e = \frac{2a^{3/2}}{\sqrt{g_0 R_E^2}} \left[2\tan^{-1}\left(\sqrt{\frac{1-e}{1+e}}\tan\frac{\phi}{4}\right) - \left(\frac{e\sqrt{1-e^2}\sin\phi/2}{1+e\cos\phi/2}\right)\right], \quad (28)$$

where R_E is the radius of the Earth, g_0 is the gravitational acceleration at the surface of the Earth and ϕ is the epicentral angle between the impact point and the point of interest (given in radians by: $\phi = r/R_E$). The ellipticity e of the trajectory of ejecta leaving the impact site at an angle of 45° to the horizontal and landing at the point of interest is given by:

$$e^2 = \frac{1}{2}\left[\left(\frac{v_e^2}{g_0 R_E} - 1\right)^2 + 1\right], \quad (29)$$

where v_e is the ejection velocity and e is negative when $v_e^2/g_0 R_E \leq 1$. The semi-major axis a of the trajectory is given by:

$$a = \frac{v_e^2}{2g_0(1-e^2)}. \quad (30)$$

To compute the ejection velocity we use the relation:

$$v_e^2 = \frac{2g_0 R_E \tan\phi/2}{1+\tan\phi/2}, \quad (31)$$

which assumes that all ejecta is thrown out of the crater from the same point and at the same angle (45°) to the horizontal.

These equations are valid only for distances from the impact site less than about 10,000 km (1/4 of the distance round the Earth). For distances greater than this the arrival time of the ejecta is much longer than 1 hour. Consequently, an accurate estimate of ejecta thickness at distal locations must take into account the rotation of the Earth, which is beyond the scope of our current program. Furthermore, ejecta traveling along these trajectories will be predominantly fine material that condensed out of the vapor plume and will be greatly affected by reentry into the atmosphere, which is also not considered in our current model. For ejecta arrival times longer than one hour, therefore, the program reports that: "little rocky ejecta reaches this site; fallout is dominated by condensed vapor from the projectile."

The mean fragment size is determined using an empirical law for the mean diameter of impact ejecta d (in meters) on Venus as a function of distance from the crater center r (in km) [Schaller and Melosh, 1998]:

$$d = d_c\left(\frac{r_c}{r}\right)^{\alpha}, \quad (32)$$

where r_c is the crater radius (in km); $\alpha = 2.65$; and $d_c = 2400 r_c^{-1.62}$. This relation neglects the effects of wind transportation, making the uncertainty in predictions greater with decreasing fragment size and distance from the impact point. It should also be emphasized that this value is a rough mean value of the ejecta fragment size. At any given location there will be a range of fragment sizes around this mean including large bombs and very fine grained dust, which will arrive at different times depending on how easily they traverse the atmosphere.

8. Air Blast

The impact-induced shock wave in the atmosphere is referred to as the air blast or blast wave. To estimate the effects of this wave we draw on data from US nuclear explosion tests [Glasstone and Dolan, 1977]. The important quantities to determine are the peak overpressure, that is, the pressure in excess of the ambient atmospheric pressure (1bar = 10^5Pa), and the ensuing maximum wind speed. With these data, tables compiled by the US Department of Defense may be used to predict the damage to buildings and structures of varying constructional quality, vehicles, windows and trees.

To compute the peak overpressure we assume that the impact-generated shock wave in air is directly analogous to that generated by an explosive detonated at the ground surface (surface burst). For a 1 Kiloton (KT) surface burst the empirically defined decay of peak overpressure p (in Pa) with distance d_1 (in m) is given by [Glasstone and Dolan, 1977, Fig. 3.66; p. 109]:

$$p = \frac{p_x}{2}.\frac{r_x}{d_1}.\left(1 + \frac{r_x}{d_1}\right), \tag{33}$$

where the pressure p_x at the crossover point from the $\sim 1/r^2$ behavior to the $\sim 1/r$ behavior is 0.69 bars (69000 Pa); this occurs at a distance of 300 m.

Yield scaling implies that a specific overpressure occurs at a distance from an explosion that is proportional to the cube root of the yield energy. This means that for two explosions of energy W_1 and W, the ratio of the distances from the explosion point d/d_1 at which the same overpressure is experienced is given by:

$$\frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3}. \tag{34}$$

Thus, to compute the overpressure at a distance r from an impact of yield energy W (in KT) we first calculate the distance d_1 away from a 1 KT explosion where the same overpressure is experienced using:

$$d_1 = \frac{r}{W^{1/3}}, \tag{35}$$

and insert this result into Equation 33. We use the data presented in Table 4 to assess the extent of the air blast damage.

The characteristics of a blast wave in air at the shock front are uniquely related by the Hugoniot equations when coupled with the equation of state for air. The particle velocity (or peak wind velocity) behind the shock front u is given by:

$$u = \frac{5p}{7P_0}.\frac{c_0}{(1 + 6p/7P_0)^{1/2}}, \tag{36}$$

where P_0 is the ambient pressure (1 bar), c_0 is the ambient sound speed in air (330 ms^{-1}) and p is the overpressure [Glasstone and Dolan, 1977, p. 97]. If the calculated maximum wind velocity is geater than 40 m/s the program reports that “About 30 % of trees are blown down; the remainder have some branches and leaves blown off.” If the maximum wind velocity is greater than 62 m/s the program outputs that: “Up to 90 percent of trees blown down; remainder stripped of branches and leaves.”

The blast wave arrival time is given by:

$$T_b = \int_0^r \frac{dr}{U(r)}, \tag{37}$$

where U is the shock velocity in air, given formally by:

$$U(r) = c_0 \left(1 + \frac{6p(r)}{7P_0}\right)^{1/2}. \tag{38}$$

For convenience, however, we assume that the shock wave travels at the ambient sound speed in air c_0. In this case, the air blast arrival time at our specified distance r is simply:

$$T_b = \frac{r}{c_0}. \tag{39}$$

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Table 4. Air Blast Damage

d_1	p (bars)	Description
126	2.78	Cars and trucks will be largely displaced and grossly distorted and will require rebuilding before use.
133	2.53	Highway girder bridges will collapse.
149	2.09	Cars and trucks will be overturned and displaced, requiring major repairs.
155	1.96	Multistory steel-framed office-type buildings will suffer extreme frame distortion, incipient collapse.
229	1.04	Highway truss bridges will collapse.
251	0.91	Highway truss bridges will suffer substantial distortion of bracing.
389	0.47	Multistory wall-bearing buildings will collapse
411	0.44	Multistory wall-bearing buildings will experience severe cracking and interior partitions will be blown down
502	0.33	Wood frame buildings will almost completely collapse.
549	0.29	Interior partitions of wood frame buildings will be blown down. Roof will be severely damaged.
1750	0.069	Glass windows shatter.

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