The Pulverization of Concrete in WTC 1 During the Collapse Events of 9-11

By

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1.0 Introduction

The collapse of the Twin Towers, seen live on TV in those unforgettable images flashed around the world on September 11th 2001, was made all the more spectacular by the vast quantities of dust and debris that were dispersed over the skyline of Lower Manhattan. Indeed, the fine grayish-white dust that covered everything within many city blocks of ground zero and the granular appearance of the rubble pile suggest that much of the hundreds of thousands of tons of material in the Twin Towers was completely pulverized.

Former BYU Prof. S. Jones in his much debated article "*Why Indeed Did the WTC Buildings Collapse?*", (available at www.scholarsfor911truth.org), states that: " *the horizontal ejection of structural steel members for hundreds of feet and the pulverization of concrete to flour-like powder, observed clearly in the collapses of the WTC towers, provide evidence for the use of explosives*… ." Unfortunately, as far as I can tell, Jones has never explained *why* pulverization of concrete could not be a natural consequence of a gravity driven collapse of WTC 1 & 2.

By comparison, F. Greening in his article "*Energy Transfer in the WTC Collapse Events of September 11th 2001*" and subsequent *Addendum*, (available at www.911myths.com), has presented arguments to show that the pulverization of WTC concrete was in fact quite possible *without the assistance of pre-planted explosives*. Nevertheless, a continuing flow of articles expressing skepticism over the "official story" of 9-11 shows that the counter argument that the energy released by the collapse of WTC 1 & 2 was insufficient to "totally" pulverize the concrete, *is still being presented as evidence that the Twin Towers were brought down by controlled demolition*.

It should be pointed out, however, that the 9-11 skeptics are apparently unable to offer any quantitative evidence that the observed pulverization of concrete in the collapse of the Twin Towers required pre-planted explosives. Therefore, to help resolve this dichotomy of opinion it is important to ask: are there any *experimental data* available to support the claim that concrete in the WTC could have been pulverized by gravity driven impact as opposed to explosive blasting?

In this report we address these questions and after considering the available evidence conclude that the pulverization of WTC concrete by gravitational collapse of each tower was indeed quite possible. Furthermore, we show that the predicted concrete particle size distribution is consistent with observations of the concrete debris at, and adjacent to, ground zero.

2.0 The Specific Energy of Concrete Pulverization in WTC 1

In this report we will focus on the collapse of WTC 1 since the upper section of this Tower had much <u>*less*</u> kinetic energy available to pulverize concrete than the energy available from the collapse of WTC 2. It follows that the energy budget for the collapse of WTC 1, compared to WTC 2, represents the more stringent test of the "natural collapse" hypothesis. In other words, if the available evidence demonstrates that the collapse of WTC 1 released sufficient energy to account for the observed pulverization of the concrete in the building, *the collapse of WTC 2 would have been even more energetically favorable to the pulverization of concrete*.

In this report we have used data from the NIST Final Report, especially NCSTAR 1-1A, 1-2A and 1-6D, whenever possible. However, for the mass of the upper section of WTC 1 we use the value 58 ? 10^6 kg taken from Z. P. Bazant and Y. Zhou's 2001 paper in the Journal of Engineering Mechanics: "*Why Did the World Trade Center Collapse? – Simple Analysis*".

We calculate the mass of concrete on each WTC 1 floor as follows:

Core floor area = 862 m^2

Out-of-core (Office space) floor areas:

2 long one-way slabs = 1,225 m^2
2 short one-way slabs = 486 m^2
4 two-way slabs = 1,137 m^2

Total out-of-core area = 2848 m^2

The floors in the core areas were made of normal weight concrete, density 1760 kg/m^3

The floors in the office areas were made of lightweight concrete, density 1500 kg/m^3

Volume of 5-inch normal weight concrete per floor = 109.5 m^3

Weight of normal weight concrete per floor = 193 tonnes

Volume of 4-inch thick lightweight concrete per floor = 289.4 m^3

Weight of lightweight concrete per floor = 434 tonnes

Total weight of concrete on one floor of WTC 1 = 627 tonnes

As described in some detail in Greening's "*Energy Transfer in the WTC Collapse*" the concrete on the 95th floor of WTC 1 was impacted by the mass of the 15-storey block of floors above the aircraft impact zone. In order to determine the energetics of this collapse we note that the drop distance was 3.7 meters and with the relation v = ?(2gh) we find the impact velocity, v_i, was 8.52 m/s. Then, using Bazant's value for the mass of the upper section of WTC 1, M_{15} = 5.8 ? 10^7 kg, the kinetic energy of the falling mass at the moment of impact is given by:

$$E = ½ M_{15} v_i^2 = 0.5 ? 5.8 ? 10^7 ? (8.52)^2 \text{ Joules} = 2.1 ? 10^9 \text{ Joules}$$

Thus we see that the first major energy transfer in the collapse of WTC 1 occurred when 2.1 gigajoules of kinetic energy was delivered to the 627 tonnes of concrete on the first impacted (~95th) floor. We now consider how concrete would behave under this degree of impact loading.

In order to compare the behavior of different materials under impact loading and other damaging events such as explosions, we need to consider the *mass specific energy input*, E_i, imparted to the material, defined as *the energy input per unit mass*. Thus for the particular case of the WTC 1 collapse we determine E_i (with the *gram* as the unit of mass) as follows:

$$\mathbf{E_i = (2.1 \times 10^9) / (0.627 \times 10^9) \text{ J/g} = 3.36 \text{ J/g}}$$

Thus we conclude that the mass specific energy input of the first impact of the upper section of WTC 1 on the layer of concrete on the 95th floor was 3.36 joules per gram. This level of energy input will now be evaluated by comparison to published data on the energetics of a wide range of impact phenomena in order to establish:

? Is a ~ 3 J/g impact potentially damaging to concrete? And, if so, what degree of concrete pulverization is to be expected from such an impact?

3.0 The Impact Loading of Brittle Materials

The impact strength of concrete and other brittle materials such as rocks, minerals, glass and ceramics, has traditionally been determined by a number of techniques:

? **The Drop Hammer:** See for example: B. P. Hughes, "*Concrete Subjected to High Rates of Loading in Compression.*" Magazine of Concrete Research 24, 25, (1972) and P. H. Bischoff et al. "*Impact Behavior of Plain Concrete Loaded in Uniaxial Compression.*" Journal of Engineering Mechanics 121, 685, (1995)

? **The Ballistic Pendulum:** See for example: H. Green, "*Impact Strength of Concrete.*" Proceedings of the Inst. of Civil Engineers 28, 383, (1964) and B. P. Hughes et al. "*The Impact Strength of Concrete Using Green's Ballistic Pendulum.*" Proceedings of the Inst. of Civil Engineers 41, 731, (1968).

? **The Split Hopkinson Bar:** See for example: B. Lundberg "*A Split Hopkinson Bar Study of Energy Absorption in Dynamic Rock Fragmentation.*" International Journal of Rock Mechanics and Mineral Science 13, 187, (1976) and C. A. Ross et al. "*Split Hopkinson Pressure Bar Tests on Concrete and Mortar in Tension and Compression.*" ACI Materials Journal 86, 475, (1989).

All these techniques involve a projectile (hammer) of known mass and kinetic energy striking a fixed target (concrete or rock sample). The effects of the impacts are usually monitored by the recoil behavior of the system and other experimental aids such as strain gauges and high-speed photography. See for example: S. Mindess, "*A Preliminary Study of the Fracture of Concrete Beams Under Impact Loading Using High Speed Photography.*" Cement and Concrete Research 15, 474, (1985).

A survey of the literature quoted above shows that most researchers used hammers or equivalent projectiles with masses in the range 3 to 350 kg dropped from heights in the range 0.2 to 3.5 meters. The actual combinations of hammer mass and drop height were such that impact kinetic energies in the range 10 to 2000 joules were investigated. In addition, because samples with weights from 20 grams to 70 kilograms were impacted, data and impact behavior for mass specific energy inputs between 0.02 and 0.9 J/g are available in the above references. *<u>These data show that significant fracturing of concrete occurs at impact energies above 0.1 J/g</u>*.

The fact that concrete is observed to fragment from impact energies ~ 0.1 J/g is consistent with the known properties of brittle materials. Thus the total *elastic* strain energy, U_s, that may be stored in a material of mass M, up to the point of the initiation of fragmentation is given by the relation:

$$U_s = ?_y^2 M / 2?E$$

where,

> $?_y$ is the yield stress
> ? is the density
> E is Young's Modulus

(See for example: T. Waza et al. in "*Laboratory Simulation of Planetesimal Collision 2. Ejecta Velocity Distribution*" Journal of Geophysical Research 90(B2), 1995, (1985).)

Substituting appropriate values of $?_y$ (40 MPa), ? (1500 kg/m^3) and E (10 GPa) for the lightweight concrete used in WTC 1 (See Appendix A of the FEMA WTC Report: "*Overview of Fire Protection in Buildings*") we find that the mass specific elastic strain energy of concrete, or the energy *per unit mass is:*

$$U_s / M = 53 \text{ J/kg } ? 0.05 \text{ J/g}$$

This energy is half of the previously noted *experimental* impact energy (0.1 J/g) required for significant fragmentation of concrete. Thus it is theoretically predicted and experimentally verified that when an impact energy in excess of about 0.05 J/g is supplied to lightweight concrete, it ceases to behave elastically and undergoes brittle fracture.

In order to further quantify impact fragmentation of concrete we need to consider its <u>*fracture energy*</u>, G_f , defined as the energy needed to create a unit area of fracture surface. For typical, normal strength, concrete G_f is ~ 100 Joules/ m^2. (See, for example A. Hillerborg. "*Results of Three Comparative Test Series for Determining the Fracture Energy G_f of Concrete*" Materiaux et Constructions (Materials and Structures) Vol 18, No. 107, 407, (1985), or F.H. Wittmann et. al "*Probabilistic Aspects of Fracture Energy of Concrete*" Materials and Structures 27, 99, (1994).)

Because a single particle crushed into *smaller* particles exhibits a *larger* surface area, we need to multiply the fracture energy of 100 Joules/ m^2 by the total surface area of the crushed particles to determine the *minimum* energy required to produce the crushed particles. It is a *minimum* energy because we are neglecting any possible kinetic energy of the crushed particles in cases where particles are violently ejected from the original sample by the impact. This neglect of the recoil energy of the fragments is valid in cases where the impacted material is reasonably well confined to a compartment or sealed container during the impact.

By way of an example, consider a 10 cm ? 10 cm ? 10 cm cube of concrete weighing 2 kg being shattered by an impact into one thousand 1 cm ? 1 cm ? 1 cm cubes. The original cube had six faces, each with an area of 100 cm^2, so that the initial surface area was 600 cm^2. After impact, the total surface area has increased to 6,000 cm^2. Thus 5400 cm^2, or 0.54 m^2, of new surface has been created. Since the fracture energy of concrete is 100 J/m^2, 100 ? 0.54, or 54 joules of energy were required to fragment the sample.

An analysis of the data presented in the studies by Hughes, Mindess and Bischoff noted above shows that the impact energies actually employed in their studies of concrete utilized about 1000 joules to fragment a 10 cm block of concrete into 1 cm, or smaller, cubes, in which case the fragmentation process actually used only about 5.4 % of the available energy. This suggests that impact fragmentation is not a very efficient process. Nonetheless, in order to apply these concepts to the pulverization of concrete in the WTC collapse we first need to consider "real-world" particle size distributions of impact fragmented concrete and determine how fragmentation efficiency varies with the mass specific energy input.

4.0 Particle Size Distributions of Brittle Materials Fragmented by Dynamic Loading

The conversion of large blocks of a brittle material into smaller fragments by crushing, grinding, hammering, drilling, or explosive blast, - processes collectively referred to as *comminution* - has been extensively studied because of its importance in mining and quarrying. (See for example: *Proceedings of the First International Symposium on Rock Fragmentation by Blasting*, Luleå, Sweden (1983); D. A. Shockley et al. in "*Fragmentation of Rock Under Dynamic Loads*" Int. J. Rock Mechanics 11, 303, (1974); M. Kabo et al. in "*Impact and Comminution Processes in Soft and Hard Rock*" Rock Mechanics 9, 213 (1977).)

The impact fragmentation of brittle bodies by energetic collisions has also been of considerable interest to astronomers and physicists as an aid to understanding the formation and evolution of asteroids and comets. Thus a large number of reports have been published in which a variety of targets, generally in the 100 - 2000 gram size range, have been impacted by high speed projectiles to investigate the fragmentation of the target. While hard rocks such as granite have been extensively studied, softer targets, frequently assembled with cement or mortar, have also been investigated. (See for example: D. R. Davis et al. in "*On Collisional Disruption: Experimental Results and Scaling Laws*" Icarus 83, 156 (1990); T. Waza et al. in "*Laboratory Simulation of Planetesimal Collision 2. Ejecta Velocity Distribution*" Journal of Geophysical Research 90(B2), 1995 (1985).)

Through these and related studies, a considerable body of data is available on the comminution of brittle materials - from granite and basalt, through intermediate strength materials such as limestone, concrete and shale, to soft minerals such as calcite and gypsum - thereby covering a wide range of hardness and fracture toughness. What has emerged from these studies is that the fragmentation of brittle materials by fast dynamic loading using explosions and/or collisions results in a range of fragment sizes that follow a universal power law distribution. (See for example: A. Carpinteri in "*One, Two, and Three-Dimensional Universal Laws for Fragmentation due to Impact and Explosion*" Journal of Applied Mechanics 69, 855 (2002); F. Ouchterlony in "*The Swebrec Function: Linking Fragmentation by Blasting and Crushing*" Mining Technology (Trans. Inst. Min. Metall. A) 114, A29, (2005).)

In his classic early paper on comminution theory, R. J. Charles showed that only *two* independent parameters, a size modulus and an energy factor, are sufficient to characterize most particle size distributions. (See R. J. Charles in "*Energy-Size Reduction Relationships in Comminution.*" Trans. AIME 208, 80, (1957)).

Thus, a commonly used size distribution function, first proposed by R. Schuhmann, is usually expressed by:

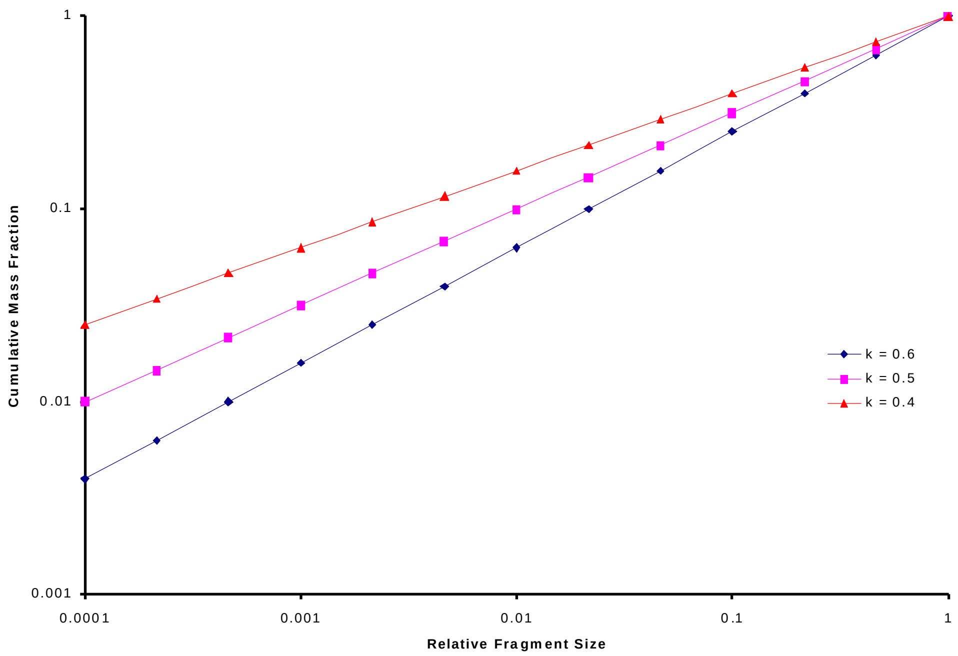
$$M\,(<d) \,/\, M_t = (d \,/\, d_{max})^k$$

Where:

d is the diameter of a specified fraction of all the particles
d_{max} is a size modulus denoting the *largest* particles in the distribution
$M\,(<d)$ is the total (cumulative) mass of fragments of size smaller than d
M_t is the *total* mass of all the particles from an impacted solid target
k is a numerical constant related to the energy imparted to the material

A log-log plot of Schuhmann's function yields a straight line of slope k as illustrated in Figure 1 where the function is shown for three values of k, (0.6, 0.5 and 0.4) that are in the appropriate range for concrete-like materials undergoing hard impact.

Figure 1. Fragmentation of Concrete-Like Materials: Cumulative Mass Fraction vs. Relative Fragment Size



It should be noted that the Schuhmann function is not particularly accurate, (or even meaningful!), as M (<d) / M_t approaches 1.0. However, this in no way detracts from the usefulness of this formalism because a number of investigators have shown that for a mass-specific kinetic energy input ~ 3 J/g, the ratio of the <u>*largest*</u> fragment mass to the total mass of the target is about 0.1. (See for example: A. Fujiwara et al. "*Destruction of Basaltic Bodies by High-Velocity Impact.*" Icarus 31, 277 (1977); D. R. Davis et al. "*On Collisional Disruption: Experimental Results and Scaling Laws.*" Icarus 83, 156 (1990).).

The Schuhmann function is also not very accurate as M (<d) / M_t approaches zero. Inspection of particle size data for materials fragmented by impact shows that the Schuhmann function *over-estimates* the amount of "fines" in a sample – the "fines" in the present context corresponding to particles smaller than about 10 microns. As a result, most "real-world" particle size distributions show a distribution that falls significantly *below* the Schuhmann value of M (<d) / M_t for particles smaller than 10 microns. For this reason a lower limit of 10 microns will be used in the following discussion.

5.0 Comminution Theory and the Particle Size Distribution of WTC 1 Concrete

The results of the comminution theory presented above and applied to the pulverization of WTC concrete, where the initial mass-specific kinetic energy of the upper section of WTC 1 was 3.36 J/g, indicate that the first experimental point on a Schuhmann function plot of crushed concrete would be for M (<d) / M_t equal to 0.1. We also note that the *initial* size metric of WTC concrete is the *shortest* characteristic length of the material as used in the buildings, which is about 10 cm. Thus, on the basis of first order comminution theory, the *largest* WTC concrete fragments are predicted to be approximately 1 cm in diameter.

A well-known approach to further classifying the size distributions of crushed materials is through a series of parameters t10, t20, t50, t100, etc, which represent the cumulative weight-percent of particles passing a sieve size of d/10, d/20, d/50, d/100, etc, where d is the original size of the particles. Furthermore, t10 is traditionally selected as a convenient single measure of the fineness of a crushed sample. (See O. Genç et al. in "*Single Particle Impact Breakage Characterization of Materials by Drop Weight Testing.*" Physicochemical Problems in Mineral Processing 38, 241, (2004).)

From a survey of Genç et al's particle size data on the comminution of concrete-like materials such as cement clinker and limestone we have been able to develop a series of Schuhmann plots representing the particle size distribution of these materials fragmented over a range of impact energies from 1 to 20 J/g. For an impact energy of 3.4 J/g on concrete-like materials we find that t10, the cumulative weight-percent of particles passing a sieve size of 10 % of the material's original characteristic length, *is approximately the same for all samples studied and may be taken to be 32 ± 1 %.*

Inspection of the data in Figure 1 shows that this value of t10 corresponds to the plot with a value of 0.5 for the Schuhmann parameter k.

It may also be shown, (See Genç et al's paper), that t10 is a function of the mass specific impact energy, E_i:

$$t10 = A [1 ? \exp(?bE_i)]$$

where,

A is a constant that represents the *maximum* value of t10 for a material
b is a constant for a given material expressed in units of grams per joule.

Data reported by L. M. Tavares in his paper "*Optimum Routes for Particle Breakage by Impact.*", in Powder Technology 142, 81, (2004), show that the constant A is equal to 65 % for concrete-like materials. Since we also know that t10 is 32 % for a mass specific impact energy, E_i, of 3.36 J/g, we conclude that the constant b is 0.2 g/J for these materials.

With these values for the parameters A and b it is possible to construct Schuhmann plots for a range of values of E_i and thereby determine the expected particle size distribution for a given impact energy. In practice it is more convenient to use an *inverse* procedure in which the Schuhmann parameter k is varied in 0.1 increments between zero and one, and a t10 value determined for each value of k. The derived t10 values may then be used to calculate the associated value of the mass specific impact energy, E_i. These values are presented in Table 1 together with the associated values of E_m, the theoretical *minimum* fracture energy defined as:

$$E_m = (1 ? 10^{?3})\ G_f\ (J/m^2)\ ?\ ?\ [S_{av}(m^2/kg)] \quad J/g$$

Where,

> G_f is the previously defined energy needed to create a unit area of fracture surface and is equal 100 Joules/ m^2 for concrete.
>
> S_{av} is the average mass specific surface area, equal to $4000/d_{av}$(?m) m^2, where d_{av}(?m) is the *average* particle size in a specified mass range - the contributions from each size range being summed over the entire range down to 10 ?m.

(N.B. The derivation of the formula for S_{av} is described in F. Greening's article "*Energy Transfer in the WTC Collapse Events of September 11th 2001*".)

Substituting for G_f and S_{av} in the above equation leads to the simple relation:

$$E_m = 400/\ d_{av}(?m)\ J/g$$

Also included in Table 1 are values of the percentage of the impact energy utilized to fragment the material; the data show that this is consistently below 15 %.

Table 1: Calculated Impact Energies, E_i, and Fracture Energies, E_m, for Schuhman Parameters Between 0.9 and 0.2

Schuhmann Parameter, k	**t10 (%)**	**E_i (J/g)**	**E_m (J/g)**	**E_m / E_i (×100) (%)**
0.9	12.6	1.06	0.059	5.6
0.8	15.8	1.38	0.087	6.3
0.7	20.0	1.82	0.136	7.5
0.6	25.1	2.41	0.223	9.3
0.5	31.6	3.35	0.373	11.1
0.4	39.8	4.68	0.622	13.3
0.3	50.1	7.28	0.998	13.7
0.2	63.1	17.45	1.455	8.3

Table 1 shows that t10, (the cumulative weight-percent of particles passing a sieve size of 10 % of the material's original size), increases as k *decreases* and the impact energy, E_i, *increases*. The same trend holds true for t20, t50, t100, etc, meaning that a larger percentage of material is crushed into finer particles as the impact energy increases, as expected. However, these and similar data also show that once the impact energy exceeds about 10 J/g or three times the initial (minimum) value for the WTC collapse, *the energy consumed in fracturing the concrete, E_m, remains essentially constant at about 1.6 J/g*.

This observation suggests that the fracturing process saturates as more and more impact energy is supplied to the material because the *probability* of fracturing a very small particle by impact is much lower that the probability of fracturing a large piece of the same material. Thus crushed concrete tends towards a limiting, constant, size distribution at impact energies greater than ~ 10 J/g. For an initial 10 cm cube of concrete this limiting size distribution is (approximately):

10 cm – 1 cm	1 cm – 1 mm	1 mm – 100 μm	100 μm – 10 μm	Less than 10 μm
30 %	20 %	15 %	10 %	25 %

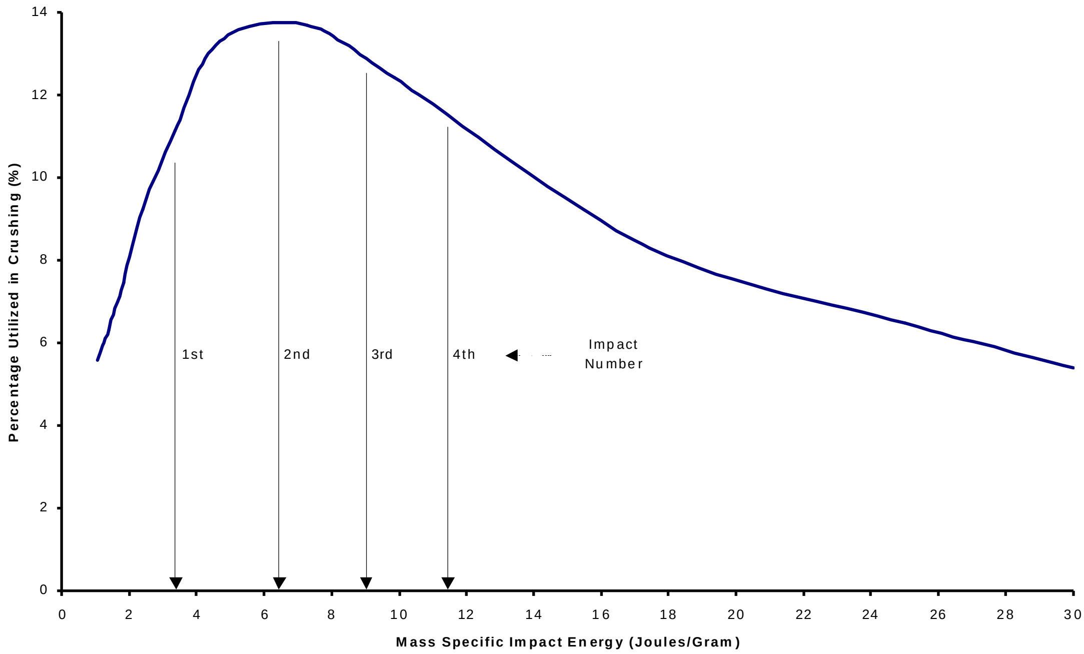
A study of the growth of the kinetic energy of the upper section of WTC 1 as the Tower collapsed shows that the mass specific impact energy of the first four collisions increased from 3.4 J/g (1^{st} impact), to 6.4 J/g (2^{nd} impact), to 8.7 J/g (3^{rd} impact), to 11.7 J/g (4^{th} impact) - See Greening's "*Energy Transfer in the WTC Collapse Events of September 11^{th} 2001*" and subsequent *Addendum*. Hence, by the 4^{th} impact, the energy supplied to the concrete was sufficient to cause it to fragment to the limiting size distribution noted above. At this point, *and for all subsequent impacts*, the energy consumed in pulverizing the WTC 1 concrete was essentially constant and progressively less than 15 % of the available impact kinetic energy as illustrated in Figure 2.

Thus we conclude that:

1. 50 % of the WTC 1 concrete was pulverized to particles less than 1 mm in diameter, (and 30 % was smaller than 100 microns).
2. For *all* impacts of the upper section of WTC 1, less than 15 % of the available impact kinetic energy was dissipated in pulverizing the concrete.

For the all-important *first impact* of the upper section of WTC 1 on the floor below (i.e. the upper section impacting the 95^{th} floor), the data in Table 1, (combined with the known 627 tonne mass of impacted material), indicate that 234 MJ of kinetic energy would have been consumed in pulverizing the concrete on the first impacted floor. In the *Addendum* to Greening's WTC Report the energy consumed in crushing the concrete on the first impacted floor of WTC 1 was estimated by an entirely different method to be 213 MJ in reasonable agreement with the present calculation.

Figure 2. Percentage of Impact Energy Utilized in Crushing Concrete



6.0 Discussion

In the first part of this report we have looked at the pulverization of WTC 1 concrete from a theoretical point of view and estimated the probable size distribution and the impact energy consumed in fragmenting the concrete on a typical WTC floor. In the following discussion we consider how well these theoretical predictions agree with direct observations of the WTC concrete as reported by researchers in the aftermath of the events of 9-11.

6.1 WTC Concrete Particle Size Distribution: Theory and Observation

Most unfortunately there appears to be no published data on the particle size distribution of samples of WTC concrete *collected directly from the rubble pile at ground zero immediately after 9-11*, although there *are* particle size data available for WTC "dust" samples collected at various locations *remote* from ground zero. As we shall demonstrate, this is an important distinction that has led to much confusion and incorrect conclusions with regard to the extent of pulverization of WTC concrete.

It is very well documented by photographs and videos of the collapse events at the WTC site that an enormous grayish-white cloud of dust and debris spread over most of Lower Manhattan on the afternoon of September 11th, 2001. Meteorological data for that time show that an approximately 5 m/s wind was blowing slightly to the west of geographic north so that the debris plume spread mainly to the south-southeast of the WTC site, (See for example, R. G. Rehm et al. in "*Initial Model for Fires in the World Trade Center Towers.*" NIST Report No. NISTIR 6879, May 2002.)

The FEMA report on Building Performance at the WTC during the 9-11 attacks includes a map showing the distribution of "heavy" collapse debris, meaning the structural steel, aluminum cladding and at least some of the concrete and gypsum wallboard. This debris was located within a circular area about ½ km wide centered at a point midway between WTC 1 & 2 and bounded by the WFC buildings to the west, Church Street to the east, Barclay Street to the north and Albany Street to the south.

By comparison, the U.S. EPA has published maps based on inspections of the exterior of buildings during the WTC site recovery operations. Buildings showing "visible dust or debris" deposits were observed at locations mainly to the south of ground zero at distances up to 1.5 km, although some buildings as far north as Chambers Street, 0.7 km from ground zero, showed evidence of WTC dust deposits. It should also be noted that airborne particulate material attributable to the WTC collapse events, which was as high as 100 mg/m^3 on 9-11, was still detectable at concentrations ~ 40 ?g/m^3 in the air over Lower Manhattan during late September 2001. However, this lingering airborne dust may be excluded from the present discussion since it represents a very small fraction, (less than 0.1 %), of the total debris produced by the destruction of buildings at the WTC.

Risk Management Solutions, Inc, (RMS) a company specializing in assessing damage and insured loss from acts of terrorism issued a Special Report on the World Trade Center Disaster in September 2001. Its major findings, which largely agree with the FEMA and U.S. EPA published information noted above, are as follows:

Massive Projectile Debris

Massive debris-related damage was caused by falling debris generated as the towers collapsed. This debris includes the bulk of building mass that disintegrated over a footprint 2 to 3 times the radius of each building's base, as well as large steel and concrete beams that, during the implosion of the towers, were ejected well beyond this footprint area. This is likely to be the principal agent of damage for most buildings near the WTC complex.

Airborne Debris

The pancake collapse of the tower floors created a major airborne "debris-surge" laden with all kinds of materials ejected in the collapse. The debris-surge cloud initially spread out at very high speeds of over 50 mph (80 km/hr). It then channeled into the surrounding canyon streets, spreading more than 1/2 mile (800 m) from the WTC site. As in a volcanic eruption, the maximum particle size decreased with distance away from the site. Close in, the airborne debris is up to 2 inches (50 mm). A thin film of dust resulting from the collapse and the ash from the fires was reported as far away as Greenwich Village – 2 miles (3,200 m) from the WTC complex.

Considering various reports and potential damage mechanisms, five damage potential zones and their distance from the WTC complex have been estimated. A detailed discussion of the damage mechanisms, potential loss levels, and exposed values in each zone follows.

Zone 1 - Collapse and Fire
Radius: 650 feet (200 meters)
Buildings and Boundaries: Includes the World Trade Center, towers 2, 3 and 4 of the World Financial Center, One Liberty Plaza, the Millenium Hotel, 90 West Street
Estimated Building Square Footage: 29.4 million (100% commercial)
Damage Description: Damage caused primarily by building collapse, fire, and massive debris surcharge onto neighboring buildings. Damage may have resulted also from the pressure wave and ground vibration. Fire ignitions are reported in at least 2 neighboring buildings. Each tower has a footprint area of 40,000 square feet (60m x 60m). Both collapses were mainly vertical with relatively minor angles of fall. The south tower collapsed in a southeast direction and the north tower in a northwest direction. Exterior structural damage is evident on buildings near the collapse zone. The majority of building mass from each tower appears to cover an area extending 650 feet (200 meters) from the center of each tower. The radius for large-sized debris extends beyond this footprint, up to 1,300 feet (400 meters) away. Thick dust up to 2 inches (50 mm) within this zone could cause major damage.

Zone 2 – Massive Debris
Radius: 1,300 feet (400 meters)
Buildings and Boundaries: Encompasses the area west of Nassau St, north of Rector St, and south of Warren St., and incorporates the rest of the World Financial Center
Estimated Building Square Footage: 6.5 million (80% commercial; 20% residential)
Damage Description: This zone is beyond the range of fire spread and damage mechanisms are primarily from falling debris, collapse, possible pressure waves resulting from the collapse, and airborne debris. Building damage is characterized by large debris falling on roofs, damaged cladding, and many broken windows. Structural damage is suspected on many buildings in this zone, and engineering surveys are being conducted. The few collapses within this zone may have been caused by the additional loads generated from debris landing on their roofs. Remaining buildings may have suffered serious roof damage as well as structural distress short of collapse. Photographs of the collapses show parabolic plumes of large pieces of debris thrown out by the collapse. There are isolated reports of missiles and debris pieces landing up to 1,600 feet (500m) away. Debris-related projectiles may cause significant damage to cladding and roofs. Dense dust over 1 inch (25 mm) within this zone could cause major damage.

Zone 3 – Thick Airborne Debris
Radius: 0.5 mile (800 meters)
Buildings and Boundaries: Encompasses most of the streets south of Chambers Street, north of Battery Park and west of Water Street; this includes the 9 to 10 block area around the WTC complex, which police cordoned off during the first week, as well as Wall Street
Estimated Building Square Footage: 72.7 million (65% commercial; 35% residential)
Damage Description: Scattered items of smaller debris and wind-blown missiles could cause damage by falling on roofs and breaking windows. Deep dust of 0.5 inches (10mm) is possible within this zone, resulting in mechanical damage (e.g. clogging to air conditioners) and damage to equipment and finishes.

Zone 4 – Thin Airborne Debris
<u>Radius</u>: 1 mile (1,600 meters)
<u>Buildings and Boundaries</u>: This area encompasses streets south of Canal St and Catherine St., including the County and U.S. courthouse areas
<u>Estimated Building Square Footage</u>: 103.9 million (65% commercial; 35% residential)
<u>Damage Description</u>: Thick dust of 0.25 inches (5mm) is possible within this zone, requiring major clean-up and resulting in mechanical damages as well as damage to equipment and finishes.

Zone 5 – Far-Field Impacts
<u>Radius</u>: 2 miles (3,000 meters)
<u>Buildings and Boundaries</u>: The northern boundary of this area is Washington Square
Estimated Building Square Footage: 85.6 million (65% commercial; 35% residential)
<u>Damage Description</u>: Light dust of 0.04 inches (1mm) is possible within this zone, requiring clean-up and possibly resulting in damages to equipment and finishes.

Risk Management Solutions' ***Zone 1***, which represents the area within 200 meters of the center of ground zero, undoubtedly contained the largest fraction of WTC debris but, with the exception of samples of structural steel, material from this location was apparently not subjected to detailed characterization. Fortunately, however, material from ***Zones 2 and 3*** *was* collected and characterized. The most detailed analyses of WTC dust from ***Zones 2 and 3*** appears to be those reported by P. J. Lioy et al. in Vol. 110, page 703, of *Environmental Health Perspectives,* J. K. McGee et al. in Vol. 111, page 972, of *Environmental Health Perspectives* , and by G. P. Meeker in the *USGS* Report No. 2005–1031. These authors collected samples shortly after 9-11 at several locations within 1 km of ground zero and carried out detailed chemical and particle size analyses; their typical findings are as follows:

(i) In addition to pulverized concrete and gypsum, the WTC dust samples contained man-made vitreous fibers (MMVF) such as slag wool and rock wool, as well as asbestos, paper, fabric, plastic and wood.
(ii) Vitreous fibers accounted for as much as 40 %, and cellulose-based material up to 10 %, of the mass of the dust.
(iii) For samples collected closest (< 400 meters) to ground zero, the particle size distribution was: 16 % greater than 300 ?m; 46 % in the range 75 – 300 ?m; 38 % less than 75 ?m.

However, data by Lioy and McGee also show that the composition of the WTC dust varied with the distance of the sampling site from ground zero. In particular, samples collected within one or two city blocks of the WTC site contained much more pulverized concrete and gypsum than samples collected at locations over 0.5 km from the site which contained more low density material such as MMVF. This result is also consistent with WTC infrared reflectance maps recorded on September 16th 2001 and subsequently reported by R. N. Clark at the USGS. These maps show that concrete and gypsum-type particulate deposition occurred mainly to the south of the WTC site and was confined to an area approximately 200 meters wide and 400 meters long.

From these observations we conclude that the WTC concrete deposition pattern was governed by two factors:

(i) The prevailing (~ 5 m/s) northerly winds on 9-11 that drove the debris cloud to the *south* of the WTC site.

(ii) The relatively *short settling time* of the pulverized concrete, consistent with its predicted particle size distribution, which meant that most of the WTC concrete was deposited within 400 meters of ground zero.

The settling time of a particle depends on its *settling velocity*, v_s, which is a function of its density and diameter, d. Values of v_s may be calculated using the approximation v_s ~ 130?d for d > 1 mm, and data from K. Wark and C.F. Warner's book *Air Pollution* for d < 1 mm. These data may be used to determine settling times for concrete particles in air.

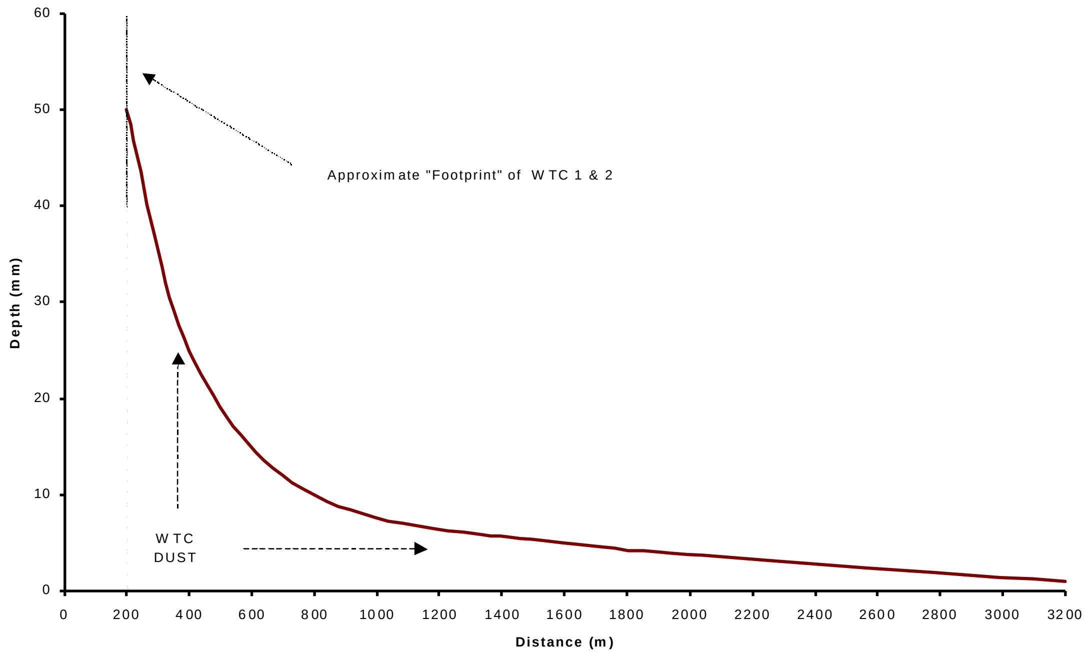
If we assume that the WTC concrete particulate was formed at an average height of 200 meters and consider how far a particle could travel in a 5 m/s wind before settling out, we may estimate the *maximum* distance the particle could be found from ground zero. Representative values are shown below together with these *maximum* distances.

Concrete Particle Diameter:	10 cm	1 cm	1 mm	100 ?m	10 ?m
Settling Time in seconds:	4	11	33	400	30,000
Max. Dist. from GZ in meters:	20	55	165	2000	-

Based on these settling distances and the expected size distribution of pulverized concrete produced during 9-11, (see Section 5.0), we conclude that almost 50 % of the WTC 1 concrete settled more than 200 meters from ground zero. However, it is important to recognize that the dust that fell well outside the footprints of the Twin Towers was a relatively small fraction of the total mass of concrete used in the construction of these buildings. To demonstrate this fact let's first consider the depth of the WTC dust estimated by Risk Management Solutions and determine *the total volume of dust produced by the collapse of the towers* , a quantity we shall call V_D.

Figure 3 is a plot of the depth of the WTC dust as a function of its distance from ground zero. It shows that the distance, x, and depth, y, follow the approximate functional form xy = a constant. This function may be integrated to determine that the total volume of rotation about the y- axis, V_T, is about 116,000 m^3. However, V_T includes a (hypothetical) volume of dust *within* the building's footprint. The volume of dust *outside* the building's footprint, V_D, may be determined by subtracting a volume equal to ?(200^2) ? 0.05 m^3 ? 6000 m^3 from V_T to arrive at a value ? 100,000 m^3 for the required volume of dust V_D. If we assume that the dust had an average density of 1200 kg/m^3 it follows that the *mass* of WTC dust was approximately 120,000,000 kg or 120,000 tonnes.

Figure 3. WTC Dust Depth vs. Distance from Ground Zero



We have previously shown that the WTC dust was made up of concrete, gypsum, man-made vitreous fiber and cellulose-based material of which only about 40 % was concrete. Thus we estimate that the collapse of WTC 1 & 2 deposited about 50,000 tonnes of concrete *outside* the footprint of the towers. If we consider that the total mass of concrete in the *two* towers was about 150,000 tonnes we conclude that 100,000 tonnes of concrete fell *within* the footprint of the towers. This has important implications for the issue of mass-shedding during the tower's collapse. It suggests that more than 90 % of the mass, (concrete and steel), in the damage zone created at each impacted floor was retained by the descending "hammer" thereby sustaining the progressive collapse of WTC 1.

6.2 The Energetics of the WTC 1 Collapse: Theory and Observation

The energy requirements for the pulverization of WTC concrete were reviewed in Section 5.0 of this report where it was estimated that 234 MJ of kinetic energy would have been consumed in pulverizing the concrete on the first impacted floor of WTC 1. Since the input kinetic energy was 2105 MJ, concrete pulverization appears to have been a relatively minor energy sink in the total energy budget of the collapse. Nonetheless, *all* the energy sinks involved in the collapse of WTC 1 need to be considered in order to determine if a self-sustaining collapse was theoretically possible. While this author has already issued several reports on the energetics of the WTC collapse events, a new, more unified approach to the factors governing collapse arrest vs. collapse propagation is presented in this Section.

The energy balance equation for each impact of the upper section of WTC 1 on the floors below is of the form:

$$\begin{aligned} E\,(\text{K. E. Input}) \quad = \quad & E\,(\text{K.E. Upper Section}) + E\,(\text{P.E. Upper Section}) \\ & + E\,(\text{K.E. Lower Section}) + E\,(\text{P.E. Lower Section}) \\ & + E\,(\text{Dissipated}) \end{aligned}$$

Thus the kinetic energy supplied by each impact is partitioned after impact into the kinetic energy of motion of the upper and lower sections of the building, the potential energy stored by elastic strain of the upper and lower sections, and the energy irreversibly dissipated by processes such as buckling, fracture, surface friction and acoustic emission. It is reasonable, as a good first approximation, to neglect the surface friction and acoustic emission components of the energy dissipation term. Furthermore we shall assume that after the elastic limit of the impacted masses is reached, and failures such as brittle fracture of the concrete and plastic deformation (buckling) of the structural steel have occurred, the *merged* mass of the impacted floor and the descending upper mass moves off as in a totally inelastic collision with velocity v_f. If the initial velocity of impact is v_i we may then write the simplified energy balance equation:

$$½\, M_n v_i^2 = ½\, [M_n + M_1]\, v_f^2 + E_d$$

where,

M_1 is the effective mass of the impacted floor.
M_n is the mass of the upper section assumed to consist of n identical floors.
E_d represents the *non-kinetic energy decrement* associated with the impact.

The WTC collapse involved a series of violent collisions where each impact event created a “damage zone’ extending *downwards* into the lower, fixed structure of the building <u>and</u> *upwards* into the upper falling section. For this reason the energy decrement term E_d must be evaluated for structural elements within this definable damage zone. Since steel and concrete account for essentially all of the structural elements in the WTC Towers we may subdivide E_d into contributions from elastic strain energy and plastic/fracture energy as follows:

$$E_d = E_e(\text{steel}) + E_e(\text{concrete}) + E_p(\text{steel}) + E_f(\text{concrete})$$

where,

E_e(steel) is the elastic strain energy stored by the structural steel up to its yield point.
E_e(concrete) is the elastic strain energy stored by the concrete up to its yield point.
E_p(steel) is the plastic strain energy dissipated by buckling of the structural steel.
E_f(concrete) is the fracture energy associated with the crushing of the concrete.

The elastic energy terms E_e for steel and concrete may be evaluated using the result given in Section 3.0 where it was shown that the mass specific *elastic* strain energy, U_s / M, that may be stored in a material of mass M, up to the point of failure is given by the relation:

$$U_s / M = ?_y^2 / 2? E$$

where,

$?_y$ is the material's yield stress
? is the material's density
E is Young's Modulus

For WTC steel: $?_y$ = 400 Mpa; ? = 7700 kg/m^3; E = 180 GPa
For WTC concrete: $?_y$ = 40 Mpa; ? = 1500 kg/m^3; E = 10 GPa

Hence, for WTC 1, the mass specific elastic strain energy capacity of steel is 57 J/kg and of concrete is 53 J/kg. If we take *one* floor as the *minimum* size of the impact damage zone for each Tower, the appropriate mass of concrete is 627,000 kg making E_e(concrete) for one floor equal to 33.7 MJ. In addition, the mass of structural steel on one floor is estimated to be 900,000 kg in which case E_e(steel) for one floor is 51.3 MJ. We have also previously shown (See Table 1) that the fracture energy associated with the crushing of concrete, is 373 J/kg in which case E_f(concrete) for one floor is 234 MJ.

Finally we need to evaluate the term E_p(steel) - <u>the plastic strain energy dissipated by the buckling of columns in the damage zone of WTC 1</u>. E_p(steel) may be estimated from the area under a load vs. vertical displacement curve for a representative WTC column. To determine an effective yielding load, F_y, for the structural steel near the 95th floor we assume that $F_y = M_{15}$ g ? "a safety factor", which we take to be 2. Thus we find that F_y = 1138 MN. We consider the collapse was dominated by core columns carrying 50 % of the structural load. Hence, the average load to failure of a core column is estimated to be 569 / 47 ~ 12 MN. An estimate of the vertical displacement to failure of a column is also needed to evaluate E_p(steel). Inspection of NIST's load displacement curves for WTC 1 show that a 0.3 m lowering within the elastic response of the core columns accounts for about 50 MJ – a conclusion that is consistent with our estimate of 51.3 MJ for E_e(steel), the <u>*elastic*</u> strain energy for one floor. The vertical displacement due to *plastic* deformation of a *single* column is about 1 meter, from which we estimate E_p(steel) for the buckling of the core columns on *one floor* to be 284 MJ.

Summarizing all the contributions to the WTC 1 energy decrement term E_d for a damage zone of <u>*one floor*</u> we have:

E_e(steel)	**= 51 MJ**
E_e(concrete)	**= 34 MJ**
E_p(steel)	**= 284 MJ**
E_f(concrete)	**= 234 MJ**
Total = E_d	**= 603 MJ**

As previously noted, a value of ~ 600 MJ for E_d is based on the collapse of *one floor* of WTC 1 and represents a *minimum* energy decrement to the input kinetic energy. However, careful observation of the initial stages of the collapse of WTC 1 reveals that some degree of *upward* crushing of the falling section accompanied the *downward* crushing of the lower section of the tower. This implies that a more realistic damage zone for the calculation of E_d should extend over *two* WTC floors, namely the uppermost floor of the lower, fixed section <u>*and*</u> the lowest floor of the descending section. On this basis we assume that the *maximum* value of the energy decrement term E_d is two times 600 MJ or 1200 MJ – a value that is still only 57 % of the input kinetic energy.

With a value of 1200 MJ for E_d we are finally in a position to evaluate the energy balance equation:

$$\tfrac{1}{2} M_n v_i^2 = \tfrac{1}{2} [M_n + M_1] v_f^2 + E_d$$

Thus, setting M_n to 5.8 ? 10^7 kg, M_1 to 0.39 ? 10^7 kg and with v_i equal to 8.52 m/s, we readily determine that the first impacted floor of WTC 1 moved off with a velocity v_f equal to 5.4 m/s; that is 3.1 m/s or 36 % slower than the impact velocity. Nevertheless, this reduced velocity was more than sufficient to guarantee a self-sustaining global collapse of WTC 1.

6.3 The Pulverization of Concrete by Explosive Blast

Although it is considered an unlikely contributor to the collapse of the Twin Towers we shall, for comparative purposes, briefly consider the energetics of concrete pulverization by explosive blast. We base this discussion on a number of reports that provide useful experimental data on blast fragmentation of concrete or similar brittle materials:

V. M. Kuznetsov. "*The Mean Diameter of the Fragments Formed by Blasting Rock.*" Soviet Mining Science Vol. 9(2), 144, (1973).

A. Rustan. "*The Influence of Specific Charge, Geometric Scale and Physical Properties of Homogenous Rock on Fragmentation.*" Proceedings of the First International Symposium on Rock Fragmentation by Blasting, page 114, (1983).

B. M. Luccioni et al. "*Concrete Pavement Slab Under Blast Loads.*" International Journal of Impact Engineering, Vol. 32, 1248, (2006).

These papers show that explosive blast is *not* a particularly effective means of pulverizing concrete especially if the explosive charges are not in direct contact with the target. Thus, for example, spherical charges of 10 kg TNT-equivalent placed 0.5 m *above* a 3 m ? 1.5 m area, 15 centimeter thick concrete slab produce a post-detonation crushed zone only about 30 cm in diameter. It is for this reason that mining and quarrying operations generally use explosive charges placed into drilled boreholes to achieve maximum fragmentation.

A. Rustan, (see reference list above), using 1.2 m ? 1.2 m area, 10 cm thick concrete blocks, showed that a specific charge (mass of explosive/volume of material fragmented) of about 20 kg/m^3 is required to reduce concrete to an average mesh size of 1 mm. Since the detonation of a 1 kg charge of TNT within a brittle material such as concrete releases about 4 MJ of chemical energy, Rustan's data indicates that only about 1 % of the available energy is directly utilized in fragmentation. This should be compared to the impact-induced fragmentation of concrete where we have shown the energy utilization efficiency is over 10 %. It follows that, *without the help of gravitational collapse*, the degree of pulverization observed during the collapse of WTC 1 would have required over 600 tonnes of high explosive *pre-placed in hundreds of boreholes in the concrete*!

7.0 Summary and Conclusions

In this report the energy required to pulverize the concrete in WTC 1 has been considered in relation to other energy sinks, and the kinetic energy associated with the collapse of this building during the attacks on the World Trade Center in New York City on September 11th 2001. The report focuses on the *first impact* of the upper section of 15 floors on the lower, fixed section of 95 floors of WTC 1 - the critical initiating event of the subsequent global collapse of the structure. This impact is investigated in detail because an energy balance analysis shows that the first single floor impact in WTC 1 was the *least energetically favorable step in the destruction of either WTC 1 or 2.* Clearly, an energy excess for this impact is a necessary condition for a gravity driven collapse of the towers to become self-sustaining

It is generally assumed by civil engineers that the most important factor in an energy balance analysis of the collapse of the Twin Towers is the energy absorbed by the plastic hinge rotations of the columns in the damage zone. (See the "*Analysis of Inelastic Energy Dissipation*" section of Bazant and Zhou's 2001 paper in the Journal of Engineering Mechanics: "*Why Did the World Trade Center Collapse? – Simple Analysis*".). A focus on this particular energy absorption term is certainly valid for a collapse involving resistance only from structural steel. However, the WTC collapse involved more than simple column buckling and it is therefore more realistic, *and conservative*, to also consider energy dissipation within at least some of the large concrete elements of the structure. This is especially true in view of the asymmetric nature of the collapse of the towers, suggesting that the concrete flooring on the 95th floor was undoubtedly the first impacted area in the collapse of WTC 1.

The possibility of arresting a progressive collapse by an efficient energy absorbing device/barrier has in fact been the subject of renewed interest in studies of skyscraper safety in the wake of the WTC disaster as a number of post 9-11 studies show – see for example: D. E. Newland et al. "*Could the World Trade Center have been Modified to Prevent its Collapse?*" Journal of Structural Engineering 128(7), 795, (2002). And: Q. Zhou et al. "*Use of High-Efficiency Energy Absorbing Device to Arrest Progressive Collapse of Tall Buildings.*" Journal of Structural Engineering 130(10), 1177, (2004).

The energy absorption by concrete has been considered for a mass-specific input energy of 3.36 J/g – a value based on the known mass of concrete and input kinetic energy of the first impact event of the collapse of WTC 1. *It is demonstrated that this level of energy input is more than thirty times the energy needed to initiate brittle fracture of concrete*.

Using comminution theory and experimental data it is shown that hard impacts on concrete-like materials produce fragment size distributions that depend to a good approximation only on the original size of the impacted specimen and the mass-specific input kinetic energy. In this way it is concluded that the WTC concrete consumed less than 15 % of the kinetic energy available from the collapse and produce fragments in the size range:

10 cm – 1 cm	1 cm – 1 mm	1 mm – 100 μm	100 μm – 10 μm	Less than 10 μm
30 %	20 %	15 %	10 %	25 %

The predicted particle size distribution of WTC concrete may be compared to data on WTC dust samples collected in the vicinity of ground zero after the 9-11 attacks. Such comparisons are not straightforward, however, because WTC dust samples contain other pulverized material, such as gypsum (from wallboard) and vitreous fibers (from insulation), in addition to concrete. Furthermore, samples collected within a few city blocks of ground zero contained a higher percentage of concrete than samples collected at locations more than 0.5 km from the WTC site. This type of fractionation of the different components of WTC dust is to be expected for the atmospheric dispersion of pulverized material exhibiting the wide range of particle sizes noted above. However, regardless of the details of the concrete particle size and contribution to the WTC dust, it is concluded that 2/3rds of the concrete debris fell within the approximate footprint of the two towers.

In the final section of this report an energy balance analysis of the collapse of WTC 1 is presented and the energy consumed in crushing concrete on one floor (234 MJ) compared to other contributions to the energy dissipated by the collapse. As expected, the plastic strain energy dissipated by the buckling of columns (284 MJ) is confirmed to be the largest drain on the kinetic energy driving the collapse but clearly the energy to pulverize the concrete is comparable in magnitude. However, and more importantly, it is argued that such energy sinks should be summed over *two* WTC floors per impact to allow for the simultaneous destruction of the uppermost floor of the lower, fixed section *and* the lowest floor of the descending section. Nevertheless, such a conservative assumption still leads to an energy decrement that is only a little over one half of the input kinetic energy, thereby assuring a self-sustaining progressive collapse of WTC 1.

By way of a footnote to this report, the pulverization of concrete by explosive blast is briefly considered and it is shown that, *without the help of gravitational collapse*, the degree of concrete pulverization observed during the destruction of WTC 1 would have required over 600 tonnes of high explosives.

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