Addendum

The following material is intended to address a number of points that have been raised concerning the material presented in F. Greening's report *Energy Transfer in the WTC Collapse*, issued March 1 2005. Most importantly, the December 2003 article by J. Hoffman entitled: "*The North Tower's Dust Cloud*" is reviewed and shown to be invalid.

J. Hoffman's Expanding Dust Cloud Calculation

J. Hoffman, in his paper "*The North Tower's Dust Cloud*", argues that among the energy sources and sinks involved in the WTC collapse events, the energy needed to expand the dust cloud is by far the largest. I intend to show that while the expansion energy in question is indeed significant, it is much smaller than Mr. Hoffman's estimate of 10^{12} to 10^{13} Joules.

On page 2 of "*The North Tower's Dust Cloud*" article Mr. Hoffman makes a statement that is an essential ingredient of his calculation but which, I believe, is invalid. The statement, which I will call statement No. 1, reads:

Statement No 1

"*Given that the Twin Towers' dust clouds behaved like pyroclastic flows, ….. , it is doubtful that mixing with ambient air accounted for a significant fraction of their volume.*"

On page 3 of his article Mr. Hoffman asserts that heat energy must have been the driving force behind the dust cloud expansion and asks:

Statement No 2

"How did the mixing of the dust cloud with ambient air contribute to its size, and how can this be factored out to obtain the volume occupied by gases and suspended materials originally inside the building?'

Finally, on page 4, we read two additional statements on the same theme:

Statement No 4

"It appears that for at least a minute, the dust cloud behaved as a separate fluid from the ambient air, maintaining a distinct boundary."

Statement No 5

"*The WTC clouds inexorably advanced down the streets at around 25 mph. This is far faster than can be explained by mixing and diffusion.*"

Based on these five statements, Mr. Hoffman concludes without proof, *that all the gas and dust in each dust cloud originated from inside the appropriate WTC Tower*. While it is self evident that all the solid material making up a dust cloud

was expelled from one Twin Tower, it is totally unreasonable to assume that all the *gas* in a dust cloud came from within a Tower. But this is what Mr. Hoffman tacitly does when he calculates his "*expansion ratio*" of 3.41, (See page 5 of his article). For this expansion ratio, Mr. Hoffman concludes (via the Gas Law $V_2/V_1 = T_2/T_1$) that the temperature of the dust cloud was over 700° C! Mr. Hoffman now proceeds to calculate the heat energy needed to raise the temperature of the gas (air) and the dust by 700° C and arrives at a value of 1.44×10^{12} Joules for the air and 4.06×10^{13} Joules for the concrete dust. The reporter mentioned by Mr. Hoffman, who found himself inside the dust cloud produced by the collapse of the South Tower, would surely have roasted to death after a few seconds in a 700° C dust cloud!

The problem with Mr. Hoffman's analysis is that he treats the dust *and the gas* in the WTC debris clouds in essentially the same way. This might have some validity for *an explosion*, where the ejection velocities are in the 1000 m/s range, but not for the relatively slow expansion of the dust cloud that was actually observed. The expansion of the dust and gas from the WTC collapse was not caused by detonation accompanied by rapid heating *but by the piston-like action of each collapsing floor.*

So, how fast was the expansion of the dust cloud? Mr. Hoffman states that the dust cloud advanced at an average horizontal velocity of only about 10 m/s immediately after a tower collapse. From Section 6.0 of my report it was estimated that dust was expelled from the upper floors of a collapsing tower at a velocity ~ 20 m/s. The rate of expansion of the dust was subsequently retarded by air resistance, so Mr. Hoffman's *average* velocity of 10 m/s over the first minute of expansion is reasonable. For dust ejected from upper floors, say 300 meters above the ground, a vertical settling velocity of about 5 m/s is also quite reasonable for 60 μm particles. Thus dust formed at 300 m moving at 10 m/s would settle out after about one minute at a distance more than ½ kilometer from the base of the tower, a trajectory which is consistent with the extent of dust dispersion observed.

Let us now consider the energy imparted to the ejected concrete dust. Each tower contained an estimated 48,000,000 kg of concrete. We will assume that 10 % of the concrete, or 4,800,000 kg, was ejected as dust. For an ejection velocity of 20 m/s the kinetic energy imparted to the dust is $\frac{1}{2} \times 4{,}800{,}000 \times (20)^2$ J = 9.6×10^8 J per tower, or *8.7×10^6 J per floor*. <u>This is much less than the energy needed to collapse the support structure of one floor = 0.6×10^9 J</u>, (See Table 1 of my report).

We may also calculate the energy imparted to the gas that was expelled from the collapse of one floor. Ignoring furniture and other office fixtures, the volume of air expelled *per floor* was about 10,000 m^3. This has an approximate mass of 12,000 kg at normal temperature and pressure. For an ejection velocity of 20 m/s this air carries away only $\frac{1}{2} \times 12{,}000 \times (20)^2$ J = 2.4×10^6 J of kinetic energy per floor.

We may, of course, repeat these calculations for the higher ejection velocities estimated for the collapse of the lower WTC floors, but the energy dissipated by the ejected dust and gas will always be small compared to the energy available from the conversion of gravitational potential energy to kinetic energy of collapse.

<u>Additional Issues</u>

The question has been raised as to how concrete sitting in metal pans on each WTC floor could have been pulverized and dispersed. In answer to this question I note that in the calculations given above I assume that only 10 % of the concrete was dispersed as a fine dust. This may appear to be not enough material to account for the vast clouds of swirling dust that were observed for each WTC tower collapse; however, I would argue otherwise. First, concrete was not the only component of the dust. Crushed gypsum wallboard, glass fiber and asbestos insulation were also found in significant quantities in the dust fallout. But let's consider what 10 % of the concrete in one WTC tower represents. It is almost 5 million kilograms of material. Spread over an area of radius 1 km it provides a surface coverage of 4,800,000/3,141,590 kg/m^2 = 1.5 kg/m^2. If we assume a density for the WTC concrete of 1500 kg/m^3, we have a layer of concrete dust 1 mm thick over an area of more than 3 km^2. This, I believe, is close to what was observed after the events of 911.

I would add that 10 % of the concrete from each floor represents less than ½-inch thickness of the 4-inch layer poured to form each WTC floor. I would also suggest that the 50,000+ tonnes of material constituting the weight of the falling block of floors would be more than enough to pulverize and disperse a ½-inch layer of concrete from each impacted floor. The remaining 3-½ inches of concrete would also be partially pulverized and wind up buried in the rubble pile that formed at ground zero.

March 10th 2005: Additional Comments

1. First, I have explained what I believe to be wrong with Jim Hoffman's dust cloud theory in my addendum above. However, let me say again, Mr. Hoffman 's calculation is flawed by his *assumption* that the air in the WTC expanded to the size of the dust cloud. To be honest I find this idea to be a little ridiculous for the relatively slowly expanding WTC clouds, and something of a self-fulfilling prophecy! In order to explain *how* the air in a WTC tower was expanded by a factor of 3.41, Mr. Hoffman simply invokes an enormous heat input – one that he shows could <u>not</u> be delivered by gravitational collapse; therefore it must be recognized that the need for explosives is pretty much built into Mr. Hoffman's calculation by his unwarranted and unphysical assumptions.
2. On the question of references for the fracture energy of concrete I used a number of sources, especially articles in the journal *Materials and Structures*. Some good examples are:
   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)

   F.H. Wittmann et. al "*Probabilistic Aspects of Fracture Energy of Concrete*" Materials and Structures 27, 99, (1994)

3. On my estimation of the energy needed to collapse one floor, E_1, I agree that the value I use is not precisely known, but I show in my

report that this is not a serious issue because the collapse time is insensitive to the assumed value of E_1 over a wide range.

4. I agree that the crushing of concrete takes time and this should be included in my calculation. However, a look at the physics of this issue leads to the conclusion that the crushing of each floor was extremely rapid and the time involved may be neglected as a first, (and very good!), approximation. The impact of a rigid mass on a hard solid object produces a longitudinal compression wave that is reflected back and forth inside the object, dissipating energy. If the energy is large enough, and the object is brittle, the object will fracture. This type of destructive collision is discussed in detail in W. Johnson's book *Impact Strength of Materials*. It is also well studied in the theory of pile driving – see for example E. A. Smith *Pile Driving Analysis by the Wave Equation* in American Society of Civil Engineers Vol. 127, 1145 (1962). A key fact about the impact of objects made of hard materials such as concrete is that the effective duration of the impact is very short because a longitudinal compression wave travels at about 3000 m/s in concrete. Studies by B. P. Hughes et. al of the impact strength of concrete using a ballistic pendulum (See Proceedings of the Inst. Civil Eng. Vol. 41, 731 (1968)), show that a 4 inch block of concrete struck by a 25 lb gravity-driven hammer fractures from an impact that lasts about 0.4 milliseconds. At a descent velocity of, say, 10 m/s, the falling block of WTC floors would traverse 4 inches (or ~10 cm) in 10 milliseconds. Thus I conclude that inclusion in my calculation of the time spent in crushing a 4 inch layer of concrete would add no more than 1 millisecond per crushed floor, or increase the calculated total collapse time of a Twin Tower by only about 0.1 seconds!

5. Finally, let me say that although I have not done any calculations for other WTC structures, the collapse of WTC 7 is a problem! I say this mainly because <u>WTC 7 was not hit by an aircraft</u>; therefore I admit it is very surprising that this high-rise building should have collapsed without being subject to an aircraft impact.