Distributed Ignition Using Single-Walled Carbon Nanotubes (SWCNTs) with Applications in Aerospace and Future Automotive Engines

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Abstract: Ignition characteristics of SWCNTs with an ordinary camera flash are reported here. The ultimate goal of the work is to use SWCNT or other nanostructured materials as a means for distributed ignition in liquid rocket fuel sprays and homogeneous-charged compression ignition (HCCI) engines. The idea was originally proposed by the author in April 2003 and patented after initial investigation. Based on the initial results, it is believed that this approach enables volumetric and distributed ignition of liquid fuel sprays as was demonstrated in gaseous fuel-air mixtures. This means remote and spatial ignition within any desired region defined by the shape of the light emanating from the light source. Initial investigation reported here was concentrated on the effects of different incident light source pulse widths on minimum ignition energy (MIE) from 350-1500 nm, effects of degree of sample compactness (packing) on the ignition characteristics, effects of percent iron (Fe) content of the SWCNTs samples, and initial measurements of sound pressure level (SPL) from the photo acoustic phenomenon. Results indicate that progressively lower energy/pulse is needed to initiate ignition by shortening the flash pulse duration. For example, at pulse width of ~0.2ms, it required ~30-35 mJ/pulse to initiate ignition of the un-compacted samples in standard air whereas at ~7ms duration it needed ~80-90 mJ/pulse to achieve the same results. For lightly-compressed samples, MIE trend remains unchanged; otherwise, increases with increased compression. Results also suggest that samples with an Fe (nanometallic particle) content as low as 18% (by weight) can be ignited in air with the utilized camera flash in the reported experimental setup.

Keywords: Carbon nanotube, fuel, ignition, propulsion, nanotechnology, spray, atomization, HCCI, rocket, engine.

INTRODUCTION

Ignition is at the heart of every combustion system from hydrocarbon-fueled home heaters to combustion engines (such as reciprocating automotive engines, gas turbine engines, rockets, etc.) Although advantages of a plurality of ignition sites and their distribution during engine operation have been demonstrated in research, ignition locations in almost all applications are fixed by design (a compromise) and limited to a few points (e.g., at most two spark plugs per cylinder in automotive engines), or confined to a narrow region within the combustion chamber (e.g., in liquid rockets achieved through the flame jet approach). The ignition concept patented here has the potential to enable on-demand selection of the region in space where distributed ignition is desired and as such provides an additional engineering variable for optimization of the ignition process in engines and other applications. In this paper, after an introduction on the serendipitous discovery of the ignition of SWCNTs, its first reported use in literature for initiating ignition of a host of fuels is summarized. Then the paper focuses on reporting initial results to measure minimum ignition energy and effects of certain key parameters on the ignition characteristics of the SWCNTs. The paper concludes with a synopsis of the observed ignition behavior of the SWCNTs.

The use of nanostructured materials as an ignition source for fuels is quite new and initiated by the author within the last five years. Therefore, very little is understood about the fundamental interaction of light with nanostructure materials as it pertains to ignition phenomenon. However, the ignition of dry "fluffy" single-walled carbon nanotubes by a simple camera flash was first noticed by Ajayan *et al.* [1]. Interestingly, the ignition was discovered by accident when a graduate student intended to document his/her experiment by an ordinary flashed camera. Ignition, however, did not occur for similar materials such as multi-walled carbon nanotubes (MWCNTs), graphite powder, fluffy carbon soot, and C_{60}. This initial observation immediately attracted the author's attention as a light-weight and low-energy ignition source. The stunning part of the finding was that the ignition is brought about by way of an ordinary small camera flash unit with two AA batteries.

Braidy *et al*. [2] confirmed the flash ignition effect on SWCNTs but also reported the presence of iron oxide particles in the combustion byproducts. These were predominantly Fe_2O_3 with a small amount of Fe_3O_4. Smits *et al*. [3] conducted experiments to determine the cause for ignition of the SWCNTs. They tested three different samples: (a) as-produced SWCNTs synthesized by the HiPco process (from Carbon Nanotechnologies Inc.), (b) the same material obtained but after a purification process, and (c) 99.5% pure, 6 -10nm diameter Fe particles. The Fe nanoparticles appear to be contained within the nanotube bundles and along their exterior surfaces as a result of the manufacturing process of carbon nanotubes as they are grown catalytically on nanometallic particles. Under identical flash lighting, both the as-produced SWCNTs and the Fe powder ignited, while the purified SWCNTs showed

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no ignition. The structure of the SWCNTs had been altered by exposure to high temperature and their diameters were no longer uniform. The large increase in Fe particle size suggests that the Fe particles melted and coalesced which imply temperatures in excess of the melting point of Fe, or 1538^{o}C. It seems that radiant energy transfer from the flash to the SWCNTs and the Fe nanoparticles causes different responses, and it is likely that the heat dissipates in the highly conductive and interconnected SWCNT bundles whereas it is almost trapped locally in the Fe nanoparticles. Bare Fe nanoparticles observed on the exterior surfaces of the SWCNT bundles are most susceptible to oxidation. Sub-surface Fe nanoparticles are likely to be involved in the oxidation process as well.

Chiang *et al*. [4] describe that the carbon shells are known to be permeable to oxygen and allow oxidation of Fe nanoparticles. Smits *et al*. [3] believe that the flash ignition of SWCNTs should be attributed to the pyrophoric nature of fine Fe particles within the nanotube bundles, rather than to any property of the SWCNTs themselves. However, the SWCNTs are believed to provide a medium stabilizing these nanoparticles to prevent spontaneous initiation of ignition until they are exposed to an appropriate stimulus such as energy from an ordinary camera flash. What has not yet been determined is the mechanism by which the flash either damages the SWCNTs, exposing the Fe particles to the oxygen, or somehow makes the Fe particles more reactive.

In summary, we are far from a complete understanding of this phenomenon and in general more basic research is required. However, in this paper targeted and selected tests are presented aimed at understanding and verification necessary for future commercialization (details are given below).

Chehroudi *et al*. [5-12] demonstrated and reported the first application of the nanotube ignition in the context of the fuels, particularly those of interest to propulsion systems. In their work, they were able not only to ignite a wide range of fuels but also to demonstrate distributed ignition of the carbon nanotubes, that is, simultaneous ignition of many nanotubes exposed to the light from the flash. They also showed ignition of drops of a variety of fuels by igniting multitude of SWCNTs in fuel/air mixture around the drops, strongly suggesting the feasibility of spatial and distributed ignition of liquid fueled sprays. Fig. (**1**) shows a sample of SWCNTs mixed with a few drops of a fuel spread on surface of the glass slide and SWCNTs before the ignition, on the left image, and just after the ignition by a camera flash, on the right. The camera flash is outside the field of view. The left image of Fig. (**2**) shows a suspended drop at the tip of a needle which is extending from the right side of the image frame into and on top of a camera flash (black object). Having commercialization prospects of the work in mind, two patents (Method and Apparatus) were filed and granted. More details on the work including tests performed can be found in these references (see Chehroudi *et al*. [5, 6]).

Observation, for the first time, that some relatively-low-cost as-produced nano-structured materials can ignite fuel/air mixtures by a benign object such as an ordinary camera flash (or low-energy diode lasers) in a distributed manner is a novel and new opportunity to achieve controlled spontaneous ignition within any desired spatial volume defined by the illuminating light source. The idea in harnessing these encouraging findings was motivated by two applications. The first case is for the controlled and spatial ignition of fuel/air mixture in homogenous-charge compression-ignition engines (HCCI), and the other is in the context of the liquid rocket booster and small satellite engines. In both cases, the observed phenomenon is addressing important technological problems currently not fully resolved in corresponding fields. The HCCI application is a high-volume, high-impact, cost-sensitive one, whereas the liquid rocket engine work is a low-volume application which is not nearly as cost-sensitive and where even a small

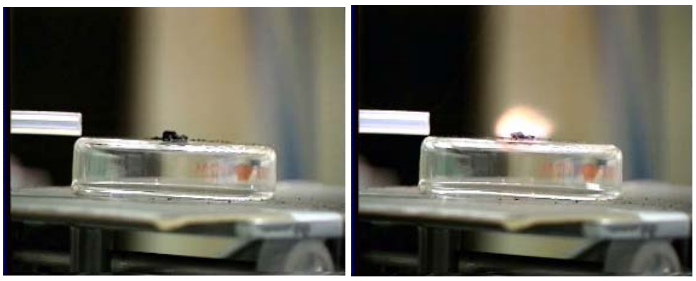

Fig. (1). SWCNTs and a few drops of a fuel before and during combustion.

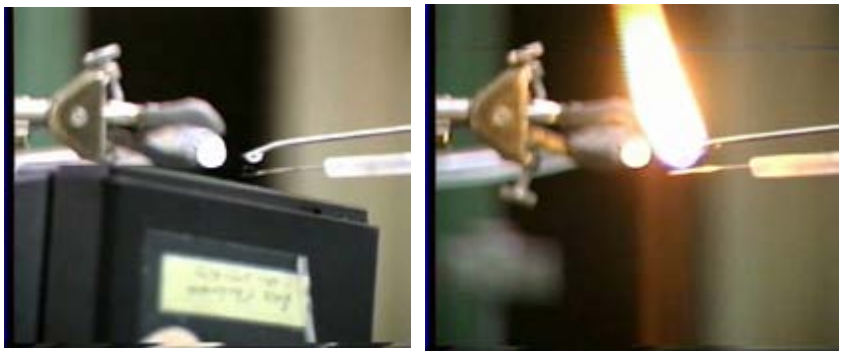

Fig. (2). Ignition of a single fuel droplet.

performance improvement at relatively high cost would be of great value to the stakeholders. Recently, and in a systematic work, this author's original ideas on distributed ignition (patent filed in 2004 and first publication available since 2005) have also been demonstrated in a homogenous fuel/air mixture, with no mention of this author's group past achievements, see Berkowitz and Oehlschlaeger [13]. The objective for the work presented in this paper is to collect adequate information on the character of the ignition process to assist intelligent application of the ideas patented.

EXPERIMENTAL SETUP AND INSTRUMENTATION

The basic experimental setup consists of either a Vivitar or a Canon camera flash, model number 730AFN and 580 XE II respectively, as ignition light source, a pulse energy meter from GenTec, SUN series EM-1 with ED-500 detector head, a sensitive microphone from Piezotronic Inc. model S05692 for detection of photo-acoustic signals, an XYZ traversing stage with a filter wheel for introducing optical filters within the light path. The light source (i.e., camera flash) was a pulsed Xe arc lamp with 0.2 and 7 ms durations at low and high light-energy settings, respectively, and was coupled to the sample area through a 3'x½" quartz fiber optic light guide from Sunoptics Technologies. A high-resolution Canon digital camera was used to capture the images of samples before and after they were exposed to a flash of light for ignition process characterization purposes. The Z-traverse (i.e., vertical) direction of the XYZ stage provided a means for incremental change in the energy-per-pulse experienced by the sample. Samples of the SWCNTs were purchased from Unidym Corp, Houston, Texas.

A complete experimental setup, part of which will be used in a continued future investigation, is shown in Fig. (**3**). It includes additional instrumentation in order to expand measurement capabilities. A high-speed pyrometer from Mikron model number KGA 740 HS from Mikron, covering 300-2300º C is used to determine the temperature of the sample as a function of time. The fiber coupled NIR spectrometer, model Symphony HR320 from Horiba, covering from 600-1400 nm is used to measure the spectral emission of the sample with and without ignition. A high-speed camera model Phantom V7.1 from Vision System which is capable of capturing up to 4000 frames/s, full screen, is used to take a snapshot of the ignition process.

The data acquisition system, model Win600 16-channel digital scope/DAQ system from Hi-Techniques, is supplemented with a photodiode detector, DET36A from Thorlabs with a rise time of 14 ns, to record the light pulse from the camera flash and also provide a TTL event synchronization pulse through a digital delay/pulse generator. The DAQ system allows the synchronization of all detection systems in addition to registration of the signal for the photometer, the pyrometer and the microphone. The entire experimental setup is housed inside a fume hood and the ventilation is turned on as needed.

EXPERIMENTAL PROCEDURE

Safety was paramount in our tests and for this reason all the necessary personal protection equipments (PPEs) such as proper gloves, respirators, head and face special tissue cover, laboratory coats, and goggles were worn. Samples of SWCNTs are carefully removed from their original containers and slowly laid on a microscope slide positioned near the end of the fiber optic cable. Then the slide was slowly pushed towards the test area where the end of the fiber optic cable is positioned. There is a grid-lined paper in the area (seen later in images of samples) which identifies the precise location of the sample and also used for length scale calibration purposes.

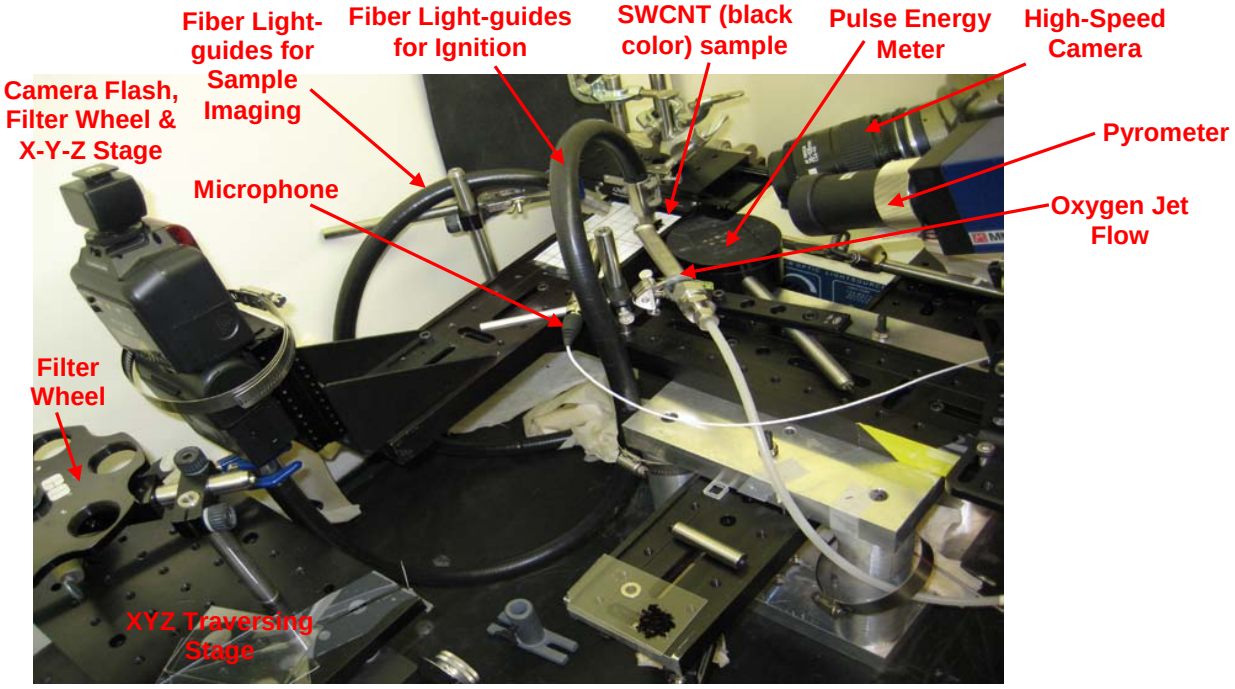

Fig. (3). Shows the experimental set up for study of the photo-ignition effect in SWCNT. The digital camera and the fiber coupling with the spectrometer are not shown. A SWCNT sample on a glass slide is also shown at the end of the fiber cable.

The output end of the fiber optic light guide is attached to a traversing stage so that it can be easily moved over the sensing area of the light energy meter for measurements of energy/pulse values. The small gap between the sensing element and the end of the fiber optic is kept the same as that distance between the fiber end and the SWCNTs sample. In this way, the energy per pulse measured by the sensor is the same as that applied to the sample. The ignition test started with an energy/pulse well below the energy required for ignition and then it was progressively increased in small steps until the onset of ignition was detected and beyond. At each step, the energy per pulse was measured and images of the sample were taken before and after the application of each flash pulse. Hence, one has detailed characterizations of the ignition process. The onset of the ignition is usually sharply and easily identifiable with both un-compacted and lightly-compacted samples.

EXPERIMENTAL RESULTS AND DISCUSSION

Ignition characteristics of SWCNTs as a function of the flash pulse duration, wavelength of light, compaction force, Fe content, and the correlation between the photo-acoustic effect and ignition process were studied. The study of ignition characteristics of compacted (or compressed) samples was performed in air and in an oxygen-rich environment. Results for each are reported below.

EFFECTS OF FLASH PULSE WIDTH AND LIGHT WAVELENGTH ON SWCNTS' IGNITION PROCESS

As-produced samples of SWCNTs with 50% (by weight) Fe contents were used for this study. These samples are "fluffy" in appearance and easily fluidized in air. For this reason, individuals handling these samples should take extra precautions to prevent inadvertent spread and human exposure.

In tests conducted here, the energy per pulse is increased progressively from a very low value and according to the procedure explained above until a sudden (and distributed) ignition at multiple locations is observed in the sample. The flash pulse energy on the sample at this point is the minimum ignition energy needed for the ignition of the as-produced SWCNTs samples. Table **1** shows a summary of the results. It was observed that regardless of optical filter in use (i.e., the selected incident wavelength region), the minimum energy/pulse needed for the onset of ignition depends only on the pulse width of the flash unit employed. This can be seen by comparing pairs of results with the same filters in Table **1**. For the low light-energy setting (corresponding to a shorter pulse width of 0.2 ms) the minimum ignition energy is mostly within 30-35 mJ/pulse and about 80-95 mJ/pulse for the high light-energy setting (corresponding to a much longer pulse width of 7 ms).

Table **1** also indicates initial results from a number of optical filters to investigate impact of the wavelength on the onset of ignition and minimum ignition energy. Data shown in Table **1** suggests that there is no sizable effect of the wavelength of light; instead, the speed with which a certain amount of light energy is delivered to the sample plays an important role. Specifically, it is shown that a lower amount of energy (~30-35 mJ) is able to initiate ignition if the sample is exposed at a shorter duration. This is intuitively reasonable because at shorter pulse duration (low light-energy setting), the energy transfer time constant is

Table 1. Measured Minimum Ignition Energy (MIE) Per Pulse and Calculated Power Per Unit Area on the Sample for Different Filters. The Same Exposure Footprints are Assumed for Both Low and High Light-Energy Settings. LP and SP Stand for Long Pass and Short Pass Filters. A Vivitar Flash was Used

	Filters Used	Photo-Ignition/ Photo-Acoustic	MIE (mJ/pulse)/ (W/cm^2)	Flash Energy Setting/Pulse Duration (ms)	Max Light Output @ This Filter & Flash Setting (mJ/Pulse)
1	No filter used	Yes/yes	85±10 /7.3 ±1.4	High /7	620
2	Same as above	Yes/yes	32±5 /255 ±40	Low /0.2	54
3	LP 495-nm, CVI	Yes/yes	83±15 /7.5	High /7	460
4	Same as above	Yes/yes	36±5 /290	Low /0.2	44
5	LP 550-nm, CVI	Yes/yes	97±15 /8.7	High /7	425
6	Same as above	Yes/yes	33±5 /260	Low /0.2	34
7	SP 1100-nm, Edm.	Yes/yes	79±15 /7.1	High /7	505
8	Same as above	Yes/yes	29±5 /230	Low /0.2	45
9	LP 700-nm, Edm.	Yes/yes	83±15 /7.5	High /7	440
10	Same as above	Yes/yes	32±5 /255	Low /0.2	39
11	SP 900-nm, Edm.	Yes/yes	85±15 /7.7	High /7	385
12	Same as above	Yes/yes	32±5 /255	Low /0.1	34
13	Many other filters	Yes/yes	80±15 /7-8	High /7	N/A
14	Same as above	No/No	Not Applicable	Low /0.2	below 30

Table 2. Minimum Ignition Energy in Air for SWCNT Samples with Different Fe Content. The High Light-Energy Setting of the Camera Flash, which also Corresponds with a Much Longer Flash Duration of 6 ms, was Used for All of the Experiments. (A Canon Flash was Used)

Fe Content of Sample (%)	Sample Appearance	Minimum Ignition Energy (mJ/pulse)
50	like soot, velvet black, fluffy	85 ± 10
45	like soot, velvet black, fluffy	91 ± 10
39	like soot, velvet black, fluffy	109 ± 10
30	like soot, velvet black, fluffy	132 ± 15
18	like soot, velvet black, extra fluffy	246 ± 20
12	gray/black powder	>1140*
5	gray/black powder	>1100*

*> 1100 or 1140 means no ignition was observed up to the estimated value shown

comparatively shorter than the time constant for energy (heat) losses from the sample, especially conduction mode, assuming same spectral coverage.

To further investigate the impact of the flash pulse width, as-produced samples of SWCNTs were exposed to a range of pulse durations (in Full-Width Half-Maximum, FWHM, sense) and results are presented in Fig. (**4**). Note the progressive reduction in MIE as flash pulse duration is reduced. Energy flux (i.e., J/s-cm^2 or Watts/cm^2) is also shown in this figure which indicates a linear relationship in this log-log graph with a very good correlation. Although a line is also considered a good fit for the entire MIE data, it appears that for longer pulse durations (> 450 μs), there is a faster (linear) drop in minimum energy when pulse duration is lowered than those tested at shorter pulse widths (< 450 μs). Assuming that spectral content of the light source and (consequently) energy transfer efficiencies to samples remain the same within the range of pulse widths studied here, the data suggests competition between two main processes, namely, rate of energy transfer versus that of energy losses from the sample to its environment.

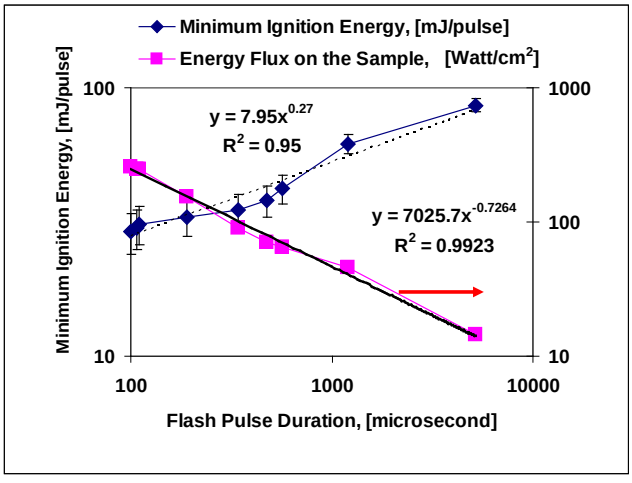

Fig. (4). Log-log plots of the minimum ignition energy and energy flux as a function of flash pulse duration for the as-produced samples of SWCNTs. The illuminated area is assumed constant for all cases (~1.13 cm^2). A Canon flash unit was used.

THE IGNITION CHARACTERISTICS OF COMPACTED SWCNT SAMPLES

In some real-life applications of SWCNTs as ignition agents, one may need to produce small pellets or films of SWCNTs by a compaction process. One wonders as to what extent the compaction process may affect the ignition characteristics of the as-produced SWCNTs. To investigate this, samples are sandwiched in between two 2"x3" microscope glass slides and a known amount of weight (or load) was applied to the sample sandwich in a uniformly distributed manner. Then the slides were separated and ignition tests performed in air and in an oxygen-rich environment using the same procedure described for samples with no compaction (i.e., un-compacted and fluffy samples). Samples with a wide range of compaction were considered and ignition characteristics for each were determined.

The ignition process was monitored and characterized by measuring the percent (or fraction) of the exposed sample area covered with "orange dots or clusters", being indicative of iron oxide particles formed due to interaction of the light and the SWCNTs sample. High-resolution images taken before and after application of each flash pulse at a given energy/pulse level combined with image processing methods enabled quantification of the observed feature (i.e., the concentration of orange dots or clusters). One distinct difference, with the exception of lightly-compacted samples, is that no abrupt or sudden ignition of the SWCNTs samples is observed, as seen for the un- compacted fluffy and lightly-compacted samples. Also the impact of the ignition process is progressive and gradual in nature. Fig. (**5**) shows the gradual ignition process in a compacted sample (10 lbf applied force) in air. These pictures are taken after exposure of 25 (left image) and 30 (right image) progressively more energetic pulses of light on the same sample. Note that the ignition process, characterized by the concentration of orange dots or clusters, slowly develops with each exposure, and the ignited region of the sample is limited to the circular footprint of the light-exposed area.

Fig. (**6**) shows plots of the fraction of the illuminated sample area that is covered with orange dots (i.e., iron oxides) as a function of the energy per pulse for high light-

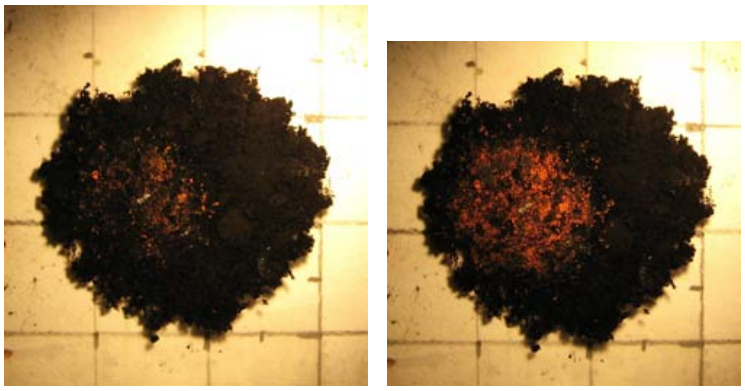

Fig. (5). Example of ignition process in a compressed or compacted sample (10 lbf weight on the slide sandwich) in air. The picture on the left is due to 25 successively-increasing flash energy exposures and the right one shows the same sample after 30 exposures. The orange area represents the region that has been illuminated by light output from the end of the fiber optic cable. Grid scale 1 centimeter.

energy setting of the camera flash with wider pulse width of ~ 7ms. The high light-energy setting was used because the need for progressively higher energy/pulse as the level of compaction increased was expected. The same set of experiments at the low light-energy setting (shorter pulse duration) was not possible, because of the much lower maximum possible output energy/pulse at this setting. Hence this investigation was limited to the high light-energy setting (long pulse duration) for this initial results. Nevertheless, it was found that the lightly-compacted samples with compression load of ~0.35 lbf exhibited the same ignition characteristics as the un-compacted fluffy samples.

As expected, it was found that samples with a higher degree of compaction required considerably higher energy per pulse in order to achieve the same concentration of the orange-colored iron oxide particles obtained by computer analysis of images (see Fig. **6**). The ignition of compacted samples, as opposed to un-compacted (fluffy) and lightly-compacted (with a compaction force of 0.35 lbf) ones, is very gradual and less well-defined. The concept of minimum ignition energy, though valid given the abrupt nature of ignition of the un-compacted (fluffy) samples, is not quite appropriate here. For this reason, images before and after each flash pulse exposure were taken and extensive image analysis performed to determine the iron oxide area fraction

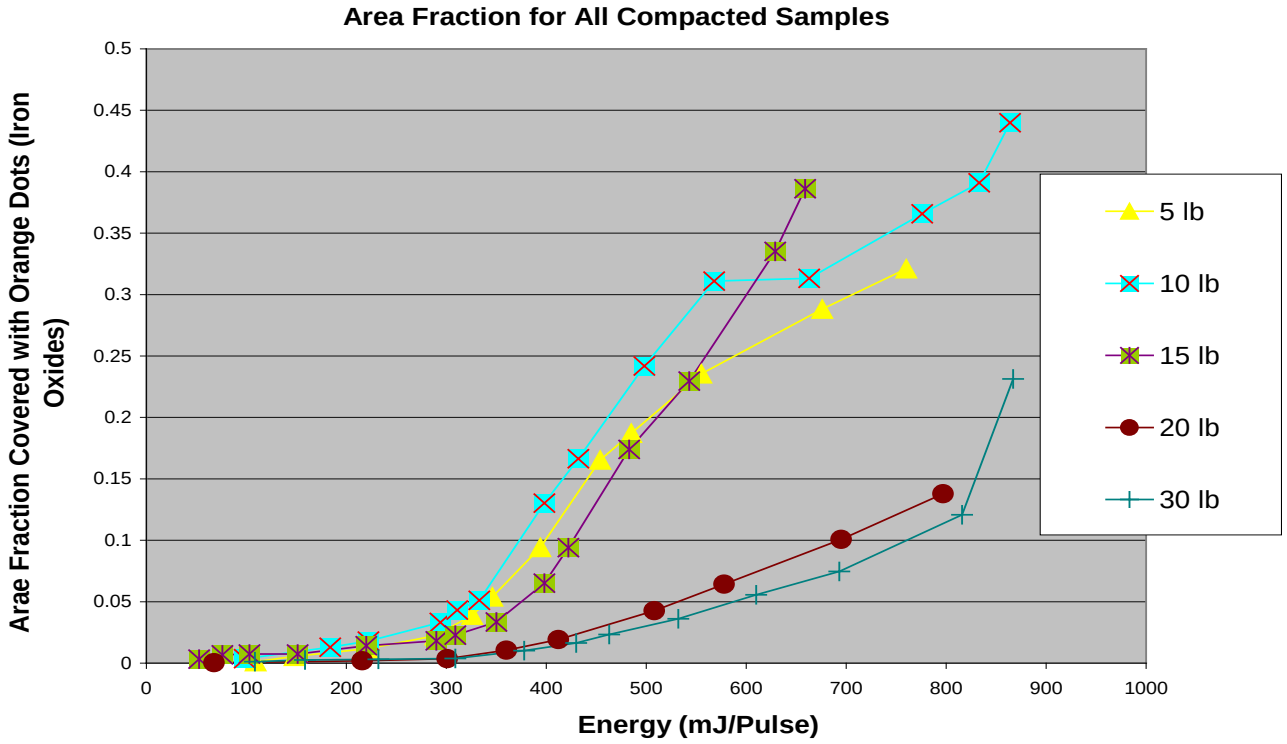

Fig. (6). Ignition characteristics of moderately and heavily compacted samples at high light-energy setting of the camera flash with pulse duration of ~7ms. These plots show the (area) fraction of the illuminated area that is covered with iron oxide (orange dots). A Vivitar flash was used.

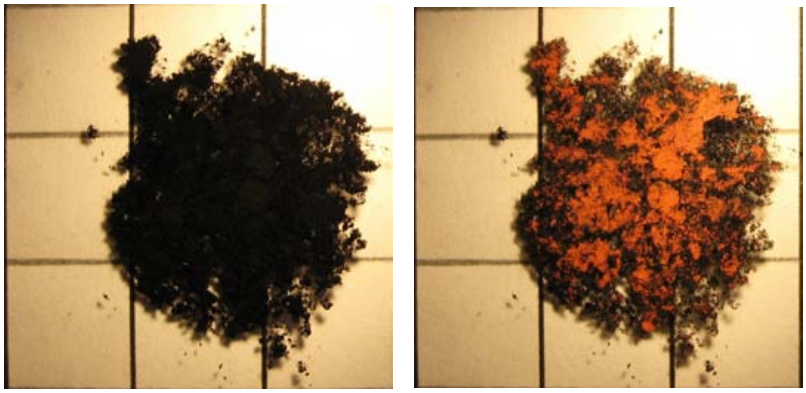

Fig. (7). Shows the observed rapid and abrupt ignition process for a compressed sample (10 lbf) in an oxygen-rich environment at the 8th (before ignition event on the left) and 9th (after ignition onset on the right) pulse when a series of pulses with increasingly more energy/pulse is used. The camera flash was at high light-energy setting (corresponding to a much longer pulse width of 7 ms). Grid size was 1 centimeter.

as it is assumed correlated with the fraction of sample ignited. The build up of iron oxide, an indication of the ignition process, is more gradual for the 5-15 lbf compaction range and it is much more gradual for the 20-30 lbf compaction force range. For example, for the latter case no detectable iron oxide regions are seen, even when up to a 400 mJ/pulse is applied.

THE EFFECT OF OXYGEN-RICH ENVIRONMENT ON IGNITION PROCESS OF COMPACTED SAMPLES

In real world applications of SWCNTs as ignition agents (e.g., liquid cryogenic rocket engines), operation in an O_2-enriched environment within certain regions of the combustion chamber is expected. Hence, effects of O_2 flow on ignition characteristics of compacted SWCNT samples were studied. The steady flow of oxygen arranged for this study, though very low, is high enough to blow the fluffy un-compacted sample away from the test area. This made tests with fluffy powders of SWCNTs almost impossible. Hence, lightly-compacted samples with a compaction force of 0.35 lbf were used as representative of uncompacted (fluffy) samples because through many tests it was convincing that their ignition characteristics were the same.

Fig. (**7**) shows a typical example of the ignition process with oxygen flowing over the samples. The ignition occurs suddenly, it covers most of the exposed surface area, and the iron oxide regions look full, more solid, and fused together compared to scattered orange particulates/clusters seen in Fig. (**5**). Note that the precise concentration of the oxygen generated by the oxygen flow as compared to standard atmosphere is not known at this stage. Hence, the purpose of the test was simply to assess gross changes in ignition behavior.

The findings show that the oxygen-enriched environment markedly improves the ignition process so that a large part of the sample ignites with a single flash above certain well-defined minimum ignition energy (per pulse). Typically, more than 50% of the surface of the sample is covered with iron oxide after the onset of ignition and it extends beyond the circular light exposure footprint defined by the diameter of the fiber light-guide. It was also found that samples with a wide range of compaction loads fully ignited within the same energy range of 110 ± 20 mJ/pulse. Fig. (**8**) shows an example of the ignition characteristic in air and in oxygen-rich environments. The abrupt nature of the ignition process under excess oxygen is clearly seen by a jump in iron oxide area fraction at about 110 mJ/pulse point.

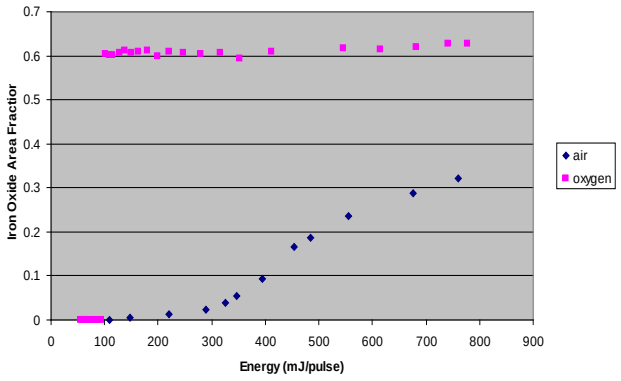

Fig. (8). Ignition characteristics of a compacted sample (compressed at 5 lbf) under air and oxygen-rich environments at the high light-energy setting. Plot shows illuminated area fraction that is covered with orange dots (i.e., iron oxides).

CORRELATION BETWEEN PHOTO-ACOUSTIC EFFECT AND IGNITION PROCESS

A systematic study of the photoacoustic effect for many SWCNTs samples was also initiated as a part of this early study. The popping sound, heard at the time of the application of each flash of light, more or less exists with or without ignition. This was recorded by a microphone and corresponding signal sound pressure level (SPL) was calculated. For each sample, the SPL was produced as a function of photon energy level, to be referred to as a photoacoustic curve. The photoacoustic behavior and photo ignition process were characterized through application of a series of flashes with successively increasing energy per pulses.

Fig. (**9**) shows the correlation between photo acoustic effect and photo-ignition for a sample that was compacted with a force of 15 lbf. The two sets of data appear to indicate the same trend in their change of slope and this happens around the region of energy where the ignition process

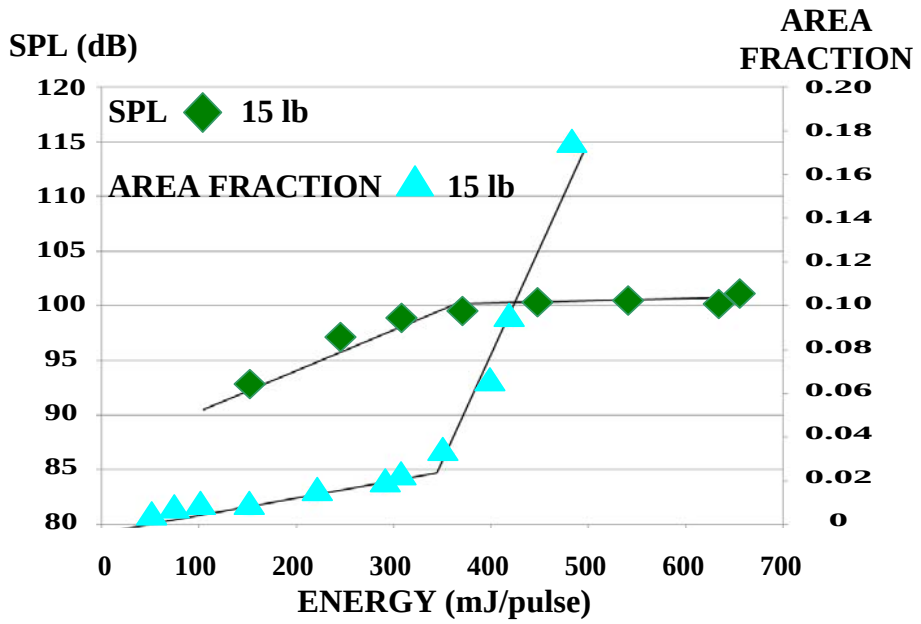

Fig. (9). Correlation between photo acoustic effect (measured as SPL) and photo-ignition for a sample with a compaction force of 15 lbf. High light-energy setting of the flash was used which also has longer pulse duration. The arrows show the corresponding axes for each curve.

accelerates. This is evidenced by the steepened slope of the line representing the iron oxide area fraction as a function of the light source energy per pulse.

THE EFFECT OF Fe CONCENTRATION ON SWCNTs IGNITION

Minimum ignition energy for four samples with different Fe concentrations was examined. In addition to Fe content, these samples look very different as well. The samples with higher Fe content are fluffy and look velvet black, while the samples with lower Fe content are granular and they look dark gray/black. The results of this study are summarized in Table **2**. Ignition of samples with an Fe content as low as 18% was achieved with the available light sources.

CONCLUSIONS

SWCNTs can be easily ignited in distributed manner with a low-level Xenon pulsed source such as a camera flash. Minimum ignition energy for the un-compacted fluffy (or very lightly compacted) samples was studied as a function of flash pulse duration. It was found that the pulse width played an important role in determining the minimum ignition energy. The shorter the light source pulse duration, the lower the minimum amount of energy necessary to bring about ignition of the as-produced samples of the SWCNTs. As expected, samples with a higher degree of compaction require considerably higher energy per pulse for ignition. Moreover, the ignition process is very gradual and less well-defined in moderately- and heavily- compacted samples. It was also found that this feature is dramatically reduced in an oxygen-rich environment. Initial investigation of the effects of the wavelength showed no noticeable change in minimum ignition energy for any wavelength region tested. However, further studies are justified and will be conducted. The photo-acoustic effect measured *via* a microphone mostly correlates with the observed photo ignition characteristics.

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