



Deflagration-to-detonation transition in natural gas–air mixtures



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ABSTRACT

The gas explosion test facility (GETF) previously used to study detonability of natural gas (NG)–air mixtures was modified for studies of flame acceleration and deflagration-to-detonation transition (DDT). The 73-m-long by 1.05-m-diameter tube was equipped with 15 baffles of varying blockage ratio (BR) = 0.13, 0.25, or 0.50, placed near the closed end of the tube and spaced 1.52-m apart. The remaining part of the tube was smooth. Experiments used mixtures between 5.1% and 15.0% NG–air.

Ignition was achieved in NG–air mixtures over the composition range 6.1–14.1%. After passing the 15 baffles, both flame and pressure wave velocity were more than 300 m/s over this range. Flame velocity was increasing over the range 6.2–12.8% NG–air, and it reached the sound speed in the burned gases (800–1000 m/s) over the composition range 8.0–10.8% NG–air. Pressure wave velocity was increasing over the composition range 6.1–14.1% NG–air and had reached sonic velocity over the composition range 6.2–12.6% NG–air. Shock waves with magnitude greater than 1 MPa were measured in all tests over the composition range 6.5–12.4%. DDT within the baffled section of the tube and sustained detonations beyond the baffles in the smooth part of the tube were observed over the composition range 8.0–10.8% NG–air. The observed run-up length to sonic flame velocity normalized by the tube diameter, X_{ru}/D , ranges from 16 to 23 at BR = 0.13, 10 to 21 for BR = 0.25, and 13 to 21 for BR = 0.50. The observed run-up length to DDT normalized by the tube diameter, X_{DDT}/D , ranges from 19 to 23 at BR = 0.13, and 16 to 23 for BR = 0.25 and 0.50.

Coal mine safety regulations in the US require mine seals to resist an explosion pressure–time curve that rises instantaneously to 0.8 MPa and remains at that level for 4 s. Pressure–time curves measured in these experiments show that shock waves with near-instantaneous rise time and magnitude greater than 1 MPa can develop from weak spark ignition after passing 15 turbulence-generating obstacles in test mixtures ranging from 6.5% to 12.4% NG–air.

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1. Introduction

Between 1976 and 2010, explosions caused by natural gas (NG) and coal dust accumulations in underground coal mines in the USA killed 186 coal miners and seriously injured many others. A total of 25 explosions involving NG and coal dust occurred in the active areas of coal mines, resulting in 165 deaths. The Scotia Mine disaster in 1976 killed 26 coal miners and rescuers, and most recently, the Upper Big Branch disaster in 2010 killed 29 miners. Another 12 explosions involving NG alone occurred between 1986 and 2006 in the abandoned and sealed areas of coal mines [1], resulting in 21 more fatalities. The Sago mine disaster in 2006 killed 12

miners; the Darby mine disaster also in 2006 killed 5 more miners, and the Blacksville mine explosion in 1992 killed 4 miners.

Completely eliminating the possibility of an NG–air explosion in underground coal mines may not be possible, since NG seeps continuously into most underground coal mines. Some of the gas emanates from the mined coal seam itself, and some flows from fissures in the surrounding rock. The mine ventilation system is designed to dilute and transport the gas out of the mine before a flammable mixture accumulates anywhere in the active mine workings. However, situations can arise where flammable mixtures of NG might develop, due to sealing of abandoned mined-out areas or to ventilation problems in active mining areas.

When mining is completed in some part of a mine, it may be partitioned off from the rest of the mine with seals that are sturdy walls or plugs designed to stop airflow into the sealed area and resist explosion pressures that could develop. The atmospheric

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composition within a sealed area starts as normal air, and as NG seeps in, a flammable mixture could form in the sealed area and exist for some period of time. Eventually, the NG concentration rises above the upper flammability limit and approaches 100%. These rich mixtures are not flammable; however, when the atmospheric pressure decreases due to a passing weather system, NG in the mined-out areas can expand into surrounding coal mine openings and possibly form a flammable mixture.

Once a flammable mixture forms, it can be ignited by a variety of uncontrolled means. The destructive power of the resulting explosion depends on the volume of the reactive mixture, its composition, and the mine geometry. Typical coal mine tunnels measure 6-m-wide and range from 1- to 4-m-high, depending on the coal seam geology. Usually, anywhere from 3 to 10 or more tunnels are excavated in parallel to mine a coal seam. The main tunnels can be several kilometers long, and they are connected every 30–60 m by additional tunnels excavated at right angles. The roof, floor, and walls of these tunnels are rough with asperities on the order of 1- to 10-cm high. Many kinds of obstructions might fill the coal mine tunnels such as mining machinery or rock supports. From a fluid mechanics perspective, coal mine tunnels have a characteristic “diameter” of about 2 m and many possibilities exist for generating turbulent flow such as wall roughness, obstructions, and intersecting flow paths.

The flame evolution in complex mine geometries can result in substantial flame acceleration. Although most accidental explosions in coal mines are deflagrations, in the worst-case scenario, the flame acceleration can lead to deflagration-to-detonation transition (DDT). The resulting detonations are extremely destructive and can induce pressures above 3 MPa. Detonations may or may not develop depending on the ability of a particular mixture composition to sustain detonations, and on the ability of flames to accelerate and produce shocks that are strong enough to ignite detonations. Even if detonations do not develop, the pressures, up to 1 MPa, generated by fast deflagrations can also be very dangerous.

The ability of NG–air mixtures to sustain detonations on large scales has been studied previously [2,3] using the Gas Explosion Test Facility (GETF) at NIOSH Lake Lynn Laboratory. In these experiments, the detonations were directly initiated in test mixtures confined in a 1.05 m diameter tube using a strong ignition source – 3–6 m³ of stoichiometric methane–oxygen mixture. Self-supporting detonations with velocities and pressures close to theoretical values were observed for mixtures containing between 5.3% and 15.6% of NG. These detonability limits are wider than previously measured on smaller scales. The detonation cell sizes varied from about 20 cm for 10% NG to 1 m or more near the limits.

In this work, we use GETF to study the ability of flames in NG–air mixtures to accelerate and produce strong shock and detonations. Flames in test mixtures are ignited using weak sparks from an electric match and propagate in a 1.05 m diameter tube fitted with baffles. The experiments aim to answer several critical questions pertinent to underground coal mine safety:

- (1) Can a weak spark ignition of a NG–air mixture develop into a detonation?
- (2) What physical conditions contribute to the flame acceleration and possible DDT?
- (3) What explosion pressures can develop in NG–air mixtures during deflagrations and detonations?

In common coal mining terminology, the gas that seeps into underground coal mines is called “methane” or “coal bed methane.” In this paper, we call this coal bed gas “natural gas” (NG), and usually use the word methane to mean chemically pure methane denoted by the formula CH₄. The composition of typical coal bed gas ranges from 82% to 99% CH₄ by volume depending on

the coal bed. It can also contain several percent nitrogen, 15% or more CO₂, and usually less than 2% ethane and other higher hydrocarbons, again, depending on the coal bed [4,5]. The NG used in these experiments came from the community NG distribution system and is similar in composition to the NG found in many coal mines. Typically, it contained about 97.5% methane, from 1.5% to 1.7% ethane, about 1% nitrogen, and trace amounts of higher hydrocarbons.

2. Prior studies of DDT in natural gas–air mixtures

Early studies of deflagrations and detonations in methane–air and NG–air mixtures produced seemingly contradictory conclusions about their ability to sustain detonation or undergo DDT. Using stoichiometric test mixtures in 2.5- and 30.5-cm-diameter tubes and ignition sources ranging from electrical discharges to 50 g of high explosive, Payman and Shepherd [6] failed to produce a sustained detonation, and concluded that methane–air seemed unlikely to support detonation. Working with test mixtures at less than atmospheric pressure (0.2–0.4 atm) and using a magnesium flare for ignition, Gerstein et al. [7] observed DDT and sustained detonation in a 61-cm-diameter tube. Using a 70 g high explosive charge for ignition in a 30.5-cm-diameter tube, Kogarko [8] observed detonation in NG–air test mixtures over a range from 6.3% to 13.5%.

In the 1970s, several research groups examined spherical detonation in unconfined NG–air clouds that could develop after a large spill of liquefied natural gas (LNG) during transport. Using various methane, oxygen, and nitrogen mixtures ignited by 2.5–520 g high explosive charges, Bull et al. [9] failed to produce detonation and concluded that at least 22 kg of high explosive would be required to initiate detonation in an unconfined cloud of stoichiometric methane–air mixture. Using a sector shock tube to simulate spherical detonation, Nicholls et al. [10] also examined various methane–air mixtures ignited by high explosive charges and concluded that about 500 g of high explosive are required to initiate detonation in an unconfined methane–air mixture. Using 5- and 10-m-diameter hemispheres of stoichiometric methane–air ignited by a spark or up to 2050 g high explosive charge, Parnarouskis et al. [11] also failed to initiate detonation and concluded that “transition from deflagration to detonation in unconfined vapor clouds does not appear to occur” and that “LNG is extremely difficult to detonate.”

Wolanski et al. [12] observed detonation over the range 8.0–14.5% methane–air in a 6.35-cm-square tube using a stoichiometric hydrogen–oxygen mixture as the ignition source. Bartknecht [13], working with stoichiometric methane–air test mixtures ignited by a flame jet, observed flame acceleration in various diameter smooth pipes. DDT was observed after 12.5 m in a 10 cm pipe, and after 18.5 m in a 20 cm pipe, but DDT was not observed in a 40 cm pipe after 30 m – the maximum length of the pipe used in these experiments. Bartknecht concluded that “the tendency to reach detonation velocity decreases with increasing pipe diameter.” Citing Payman and Shepherd [6], Bartknecht [13] stated that methane–air mixtures normally cannot be made to detonate except through the use of very powerful ignition sources. However, re-examination of Bartknecht’s data shows that the normalized distance to detonation (X_D/D) decreases from 125 to at least 75 as pipe diameter increases. This means that detonations are likely to appear in pipes of any diameter, if the pipe is long enough. Lindstedt and Michels [14] observed DDT in stoichiometric methane–air mixtures using a 5-cm-diameter tube equipped with Shchelkin spiral obstacles of BR = 0.44 and varying length at the ignition end. DDT occurred at a distance X_D of about 8 m corresponding to an X_D/D ratio of about 160.

Recent studies of flame acceleration and DDT in reactive gas mixtures have developed an understanding of necessary conditions for the onset of DDT. First, the flame must accelerate from the initial laminar flame velocity upon ignition (about 38 cm/s for stoichiometric methane–air) to a velocity equal to the local sound speed in the combustion products. For methane–air mixtures at standard atmospheric pressure and temperature, this velocity ranges from about 800–1000 m/s, depending on composition. The distance required for sonic flame velocity to develop is defined as the run-up distance, X_s . Ciccarelli and Dorofeev [15] summarize two empirical models for determining X_s as a function of blockage ratio (BR) for various gases including methane. One model [16], developed for the BR range 0.01–0.1, applies to “smooth” tubes, and the other [17], developed for the BR range 0.3–0.75, is for “obstructed” tubes. According to the first model, the run-up distance to sonic flame speed in a smooth tube (BR = 0.01) filled with a stoichiometric methane–air mixture decreases from 122 to 77 tube diameters d , when d increases from 0.1 to 1 m. These model predictions are in general agreement with experimental observations [13,18].

Once the flame has accelerated to sonic velocity, two necessary criteria apply for the onset of DDT in channels with obstacles [15] – a minimum tube diameter criterion ($d > \lambda$) and a minimum scale requirement ($L > 7\lambda$). Here λ is the detonation cell size that can vary approximately between 19 and 35 cm for stoichiometric methane–air mixtures [2,3,18–23]. The minimum tube diameter criterion ($d > \lambda$), was formulated by Peraldi et al. [24] based on experiments with hydrogen, ethylene, propane, and methane. According to this criterion, the inner diameter of the orifice plates (d) must exceed the detonation cell size (λ) to support a sustained detonation. The “ d ” could be the tube diameter for a smooth tube, or the inner diameter of orifice plates within the tube.

The minimum scale requirement ($L > 7\lambda$) was proposed by Dorofeev et al. [25], who defined the characteristic length scale for BR > 0.1 as:

$$L = \frac{(S + D)/2}{1 - d/D} \quad (1)$$

where D is the tube diameter, S is the obstacle spacing, and d is the size of unobstructed passage. According to [15,25], detonations can develop when $L > 7\lambda$.

3. Test facility

The GETF at NIOSH Lake Lynn Laboratory (LLL), previously used to study the detonability of NG–air mixtures [2,3], is modified to examine flame acceleration and DDT by adding obstructions (baffles) inside the tube. The modified facility consists of the same (1) detonation tube; (2) supporting systems for gas injection, mixing, sampling, and analysis; (3) data acquisition system; and (4) remote control system as used for prior detonation experiments. The baffle system and modified ignition system is described in detail here. Figure 1 shows a schematic of the system, and Figs. 2–4 are pictures of the facility.

3.1. Detonation tube

The GETF is a 105-cm-diameter tube with a total length of 73.2 m that is fabricated from hot-rolled and welded industrial pipe. It is tied to solid concrete foundation blocks with steel cables and anchored into a concrete buttress and earthen berm. The steel tube has a wall thickness of 9.5 mm with minimum yield strength of 248 MPa. The highest dynamic pressure recorded so far in the GETF is about 7 MPa, and the tube shows no evidence of deformation or damage.

3.2. Baffle system

Starting near the closed end, the tube was modified to add baffles with blockage ratio (BR) of 0.13, 0.25, or 0.50, spaced 1.52-m apart on center. The baffles inside the tube (Fig. 3) are made from steel H sections (W200x100). One beam placed across the tube gives BR = 0.25, and two beams give BR = 0.50. For BR = 0.13, the flanges on one side of the H section are cut off. To hold the baffles inside the tube, pairs of rectangular holes measuring about 24-cm-wide by 44-cm-high were cut across the diameter of the tube. Steel sections welded to the tube reinforce the perimeter of this hole and counteract stress concentrations that arise. Additional horizontal beams (also W200x100) welded along the outside axis of the tube provide a reaction for the baffles inside the tube (Fig. 4). Steel plates with gaskets cover these holes to keep the tube airtight. The baffles and the associated external reinforcement structure have survived the shock pressures from these explosion tests with no evidence of deformation or damage.

The baffle arrangement used in these experiments differs from orifice plates used in most prior work [23]. The practicalities of constructing baffles at the 1-m-scale with enough strength to survive the explosion forces dictated a different approach to generate turbulence and promote flame acceleration inside the tube. A major concern was rupturing the tube due to the holes cut into the tube to accommodate the baffles. To better preserve integrity of the tube, baffle spacing of 1.52 m was used. With this spacing, pressure and light sensors are located in between every other baffle set. The sensors are always in the same relative position between baffle sets.

For BR = 0.5, the baffle arrangement is symmetric (Fig. 3); however, for BR = 0.13 and 0.25, the baffle arrangement is not symmetric. The effect of this asymmetry on turbulence, flame acceleration, and possible DDT is not known.

3.3. Gas mixing and analysis

The gas mixing system enables creation of homogeneous NG–air test mixtures inside the tube at pre-determined equivalence ratios. As shown in Fig. 1, the mixing system consists of an enclosed blower fan, an intake manifold, and an injection manifold. At the beginning of a test, a 0.15-mm-thick plastic diaphragm is placed over the open end of the tube, and the required quantity of NG is injected into the intake manifold and mixed with air in the detonation tube. A sample draw system enables remote collection and analysis of the test mixture at three points – the closed ignition end, the middle, and the open end of the detonation tube. Gas mixing is stopped when the infrared analyzer readings at the sample points agree within $\pm 0.1\%$.

3.4. Ignition

The test mixture is ignited with a commercially-available electric match containing 0.45 g of pyrotechnic composition. It produces multiple weak sparks with a total released energy of about 2 kJ. The electric match is placed about 0.5 m away from the closed end of the tube.

3.5. Data acquisition system

The tube is equipped with 23 piezoelectric pressure transducers and 23 light sensors placed in pairs (pressure and light) approximately every 3 m along the length of the tube. Two separate 24-channel data acquisition devices (National Instruments CompactRIO) collect data at 50,000 samples per second or 20 μ s between samples. A channel in each data acquisition device records a

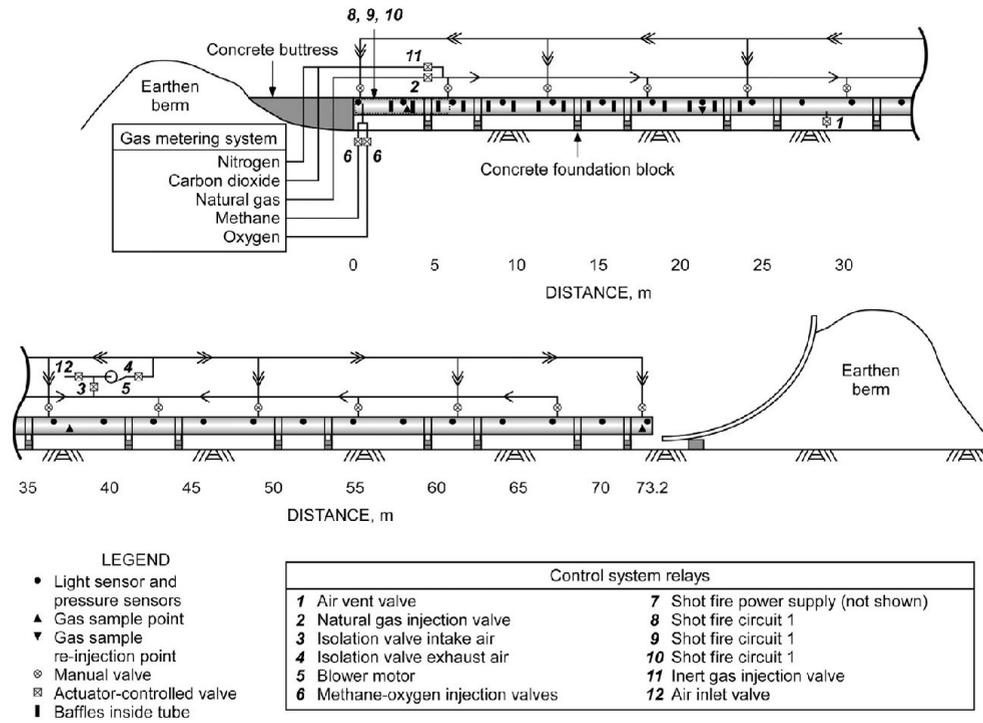


Fig. 1. Schematic of GETF with baffles.



Fig. 2. Overview of GETF showing the 73-m-long tube, mixing system, bunker housing the data acquisition system, and the control building. (Photo by NIOSH.)



Fig. 4. GETF tube showing external reinforcement structure to support baffles inside tube. (Photo by NIOSH.)



Fig. 3. Baffles inside GETF tube with BR = 0.13 (left), BR = 0.25 (middle), and BR = 0.50 (right). (Photo by NIOSH.)

synchronization signal from a signal generator. The data acquisition system is housed in a small bunker next to the tube (Fig. 2).

When using silicon phototransistors (Optek NPN OP800WSL) as flame sensors, a tradeoff exists between the rise time and magnitude of the light signal. The light sensors can be configured for either high sensitivity to light at the expense of low resolution of arrival time or high resolution of arrival time at the expense of low sensitivity to light. The nature of the signal depends on the resistor placed between the emitter and ground of the phototransistor light sensor. In these experiments involving everything from slow, low-light flame fronts through fast, bright detonation waves, a 10,000 ohm resistor provided the best balance for detecting the leading edge of flame arrival; however, resolution in the arrival time measurement decreased to about 50 μ s.

The piezoelectric pressure sensors (PCB Piezotronics CA102B04) have a range of 0–6900 kPa and 1 μ s rise time. Instead of being threaded directly into the sidewall of the detonation tube, the pressure sensors are suspended over a hole in the tube with a special anti-vibration mount. This mount shields the pressure sensor from extraneous, high-speed vibrations traveling within the steel detonation tube itself and does not adversely change the character of the desired pressure wave measurements [2,3].

3.6. Remote control system

All experimental operations are done remotely in the LLL control building located about 300 m away from the tube. For safety, the GETF has 3 independent electric shot fire circuits (8, 9, and 10 in Fig. 1) to ignite the test mixture. Firing the primary shot fire circuit (8) also triggers the data acquisition system.

4. Experimental results

A series of 31 electric match ignition tests was conducted in 2012 using the GETF starting with 9 tests at BR = 0.50, followed by 10 tests at BR = 0.25, and concluding with 12 tests at BR = 0.13. All tests had 15 baffles spaced 1.52 m apart with the first set located 2.3 m from the closed end of the tube and the last (15th) at 23.6 m. The remaining part of the tube is smooth. Table 1, arranged from leanest to richest NG–air mixtures, summarizes key data from this test program, beginning with the test identifier, composition, and BR information and followed by test data extracted from 3 of the 23 recording stations – at 5.94 m after the 3rd baffle, at 24.23 m after passing all 15 baffles, and at 73.03 near the end of the tube.

Pressure and light signals for Tests # 106, # 100, # 98, # 116, # 119, and # 113 are summarized in x – t diagrams shown in Fig. 5. These particular x – t diagrams illustrate many of the most important results from these experiments, including the composition range in which sustained detonation, shock pressure greater than 1 MPa, and supersonic flame and shock velocities were produced. Figure 5a and d shows sustained detonations for Test # 106 with 8.0% NG–air and Test # 116 with 10.8% NG–air. DDT occurred near position 22.5 m in both cases. Figure 5b and c for Test # 100 and # 98 with 8.25% and 10.55% NG–air, respectively, show that DDT occurred in both tests; however, sustained detonation did not develop due to the high BR of 0.50. Figure 5e and f show deflagrations in which DDT did not occur. In Test # 119 with 12.0% NG–air and BR = 0.13, flame speed is about 569 m/s, and maximum pressure is about 0.26 MPa at the last baffle. Beyond the baffles in the smooth part of the tube, the shock pressure increases to about 1 MPa. The flame is still accelerating, and with more baffles in the tube, it can be concluded that DDT would occur eventually. In Test # 113 with 12.4% NG–air and BR = 0.25, flame speed is about 752 m/s, and maximum pressure is about 0.95 MPa at the

last baffle. DDT has nearly developed, and again, it can be concluded that with more baffles in the tube, DDT is likely.

In Table 1, data from the station after the 3rd baffle are early in the flame acceleration process. Flame and pressure wave velocities are generally low, i.e. subsonic, although for near stoichiometric test mixtures, a pressure of 0.5 MPa was achieved. Data from the station after the 15th baffle are usually indicative of the highest flame and pressure wave velocities and the greatest pressure wave magnitude. Data from the station near the tube's end may indicate supersonic flame and pressure wave velocity and the CJ pressure if detonation develops in the baffled section of the tube. Otherwise, the data show that flame and pressure wave velocity along with pressure wave magnitude decrease in the smooth section of the tube from 23.6 m to its end at 73.23 m.

In Table 1, flame arrival time is found by first observing when the light sensor signal becomes saturated indicating full flame presence and then looking back in time to when the sensor first detects a light signal clearly above the background noise. Arrival time of the pressure wave is the time when the leading pressure wave reaches its maximum value. Early in the flame acceleration process, this arrival time will obviously lag the first arrival time of the pressure wave itself; however, once a shock wave has developed, the arrival time of the shock and the arrive time of maximum pressure are the same. Using arrival time of the maximum pressure wave facilitates a more consistent calculation of the pressure wave velocity.

On occasion, the sensors at 5.94, 24.23, or 73.02 m did not provide usable data, in which case, arrival time and maximum pressure data were interpolated from adjacent sensors if possible. Interpolated data is indicated in red in Table 1. In other cases, the sensors or data acquisition system did not provide any useful data at these sensors and their neighbors. In that case, N.A. or not available is indicated in Table 1. The flame and pressure wave velocities in Table 1 are calculated using a backward difference between the arrival times from sensors at 5.94, 24.23, and 73.03 m and those sensors 3.1 m behind.

Table 1 shows that ignition was achieved in mixtures ranging from 6.1% to 14.1% NG–air. This range, observed for the weak spark ignition using a 0.45 g electric match is smaller than the 5–16% methane in air flammability range found by Cashdollar et al. [26] or the 4.6–16.8% methane in air range used by Kuznetsov et al. [27]. Table 1 also shows that the time required for the flame to travel 5.94 m from the ignition source past 3 baffles ranged from 0.148 to 0.818 s, depending on the composition. Early in the flame acceleration process, the blockage ratio had little effect on the flame arrival time at 5.94 m. This arrival time data provides useful information for numerical model verification, especially during the initial phases as the flame evolves from laminar into a turbulent flame front. However, the early time data may be affected by inherent time delays within the electric matches.

Figure 6 shows the measured flame velocity for all tests as a function of composition after passing 3, 7, 11, and 15 baffles, and then just before the tube exit at 73.03 m. The black line in this figure is the sound speed C_{CJ} corresponding to the pressure and temperature at the CJ point computed using Fried et al. [28]. This sound speed is slightly higher than the sound speed C_f behind a slow methane–air flame at constant pressure; however, the flames in these experiments are not slow. They generate shocks, and the pressure in the burned material can be high. Therefore, the sound speed relevant for these fast flames is somewhere between C_f and C_{CJ} , and it gets closer to C_{CJ} as the flame velocity increases. Since we are interested mostly in fast flames that produce detonations, C_{CJ} provides a useful reference point for sufficient flame velocity.

The four dashed lines in Fig. 6 approximate the average flame velocity data after passing 3, 7, 11, and 15 baffles. Note that these lines are just visual approximations, with about half the data

Table 1
Data summary from 31 weak spark ignition tests with various natural gas–air mixtures.

GETF Test #	NG-air (%)	BR	Test outcome	At 5.94 m after 3 baffles					At 24.23 m after 15 baffles					At 73.03 m exiting tube					
				Flame arr. time (s)	Flame vel. (m/s)	Max. press. arr. time (s)	Press. wave vel. (m/s)	Max. press. (MPa)	Flame arr. time (s)	Flame vel. (m/s)	Max. press. arr. time (s)	Press. wave vel. (m/s)	Max. press. (MPa)	Flame arr. time (s)	Flame vel. (m/s)	Max. press. arr. time (s)	Press. wave vel. (m/s)	Max. press. (MPa)	
123	5.10	0.13	No ign.																
111	5.20	0.25	No ign.																
124	6.10	0.13	Deflag.	N.A.	N.A.	1.30500	8	0.00	1.53077	343	1.53600	280	0.10	1.71072	251	1.60800	643	0.16	
112	6.20	0.25	Deflag.	0.53972	11	0.54768	45	0.05	0.58874	565	0.59056	1151	0.54	0.76164	271	0.65786	609	0.17	
101	6.50	0.50	Deflag.	0.64776	342	N.A.	N.A.	0.24	0.68472	543	0.68132	700	1.13	0.80556	353	0.75566	613	0.35	
107	6.70	0.25	Deflag.	0.46786	80	0.47578	12	0.05	0.51253	556	0.51008	894	1.55	0.63232	398	0.57396	639	0.24	
125	7.10	0.13	Deflag.	0.40930	44	0.39964	15	0.04	0.45998	561	0.46144	840	1.01	0.59328	395	0.51994	684	0.38	
97	7.32	0.50	Deflag.	0.25976	23	N.A.	N.A.	0.21	0.28764	583	0.28706	824	0.86	0.39392	433	0.35640	658	0.27	
126	8.00	0.13	Deflag.	0.20094	83	N.A.	N.A.	0.08	0.24784	750	0.24634	832	1.29	0.35664	500	0.30586	713	0.26	
106	8.00	0.25	Sus. Det.	0.26988	22	0.27182	22	0.08	0.29548	1640	0.29642	2049	7.60	0.32332	1761	0.32420	1741	3.01	
100	8.25	0.50	DDT	0.23734	415	0.23948	25	0.37	0.26368	925	0.26418	1000	1.57	0.35148	476	0.32666	726	0.63	
105	8.80	0.25	Sus. Det.	0.20710	160	0.21014	28	0.20	0.22830	1589	0.22916	1714	7.60	0.25600	1835	0.25642	1776	1.74	
127	9.10	0.13	DDT	0.22432	104	0.22726	26	0.07	0.26458	812	0.26298	875	1.88	0.31908	1054	0.31676	815	1.26	
95	9.54	0.50	Sus. Det.	0.16832	484	0.16888	35	0.51	0.19010	2773	0.19200	1292	1.76	0.21872	1643	0.21904	1808	2.14	
96	9.67	0.50	Sus. Det.	0.14884	514	0.14828	40	0.32	0.17260	1315	0.17328	1315	6.13	0.20026	1587	0.20052	1787	1.87	
117	10.00	0.13	Sus. Det.	0.17460	97	0.17864	33	0.07	0.21368	839	0.21260	966	2.12	0.23876	1797	0.23938	1813	2.86	
104	10.10	0.25	Sus. Det.	0.20350	29	0.20518	497	0.16	0.22428	1773	0.22480	1909	3.66	0.25082	1846	0.25166	1808	2.20	
98	10.55	0.50	DDT	0.14816	40	N.A.	N.A.	0.22	0.17410	1135	0.17534	803	1.49	0.26884	485	0.23970	671	0.34	
116	10.80	0.13	Sus. Det.	0.22344	132	N.A.	N.A.	0.14	0.25350	1365	0.25438	1556	4.24	0.28012	1693	0.28088	1813	1.88	
118	10.80	0.13	Deflag.	0.21002	70	N.A.	N.A.	0.15	0.25962	604	0.25874	866	1.36	0.35554	407	0.31414	736	0.60	
99	11.26	0.50	Deflag.	0.24458	132	N.A.	N.A.	0.21	0.28308	530	0.27722	816	1.25	0.37596	460	0.34758	651	0.30	
119	12.00	0.13	Deflag.	0.36374	47	0.39318	32	0.03	0.43384	569	0.43992	391	0.26	0.55654	427	0.49736	732	0.46	
113	12.40	0.25	Deflag.	0.32442	18	0.33148	18	0.05	0.36566	752	0.36668	832	0.95	0.49342	338	0.42834	656	0.46	
103	12.59	0.50	Deflag.	0.81828	854	0.79506	7	0.02	0.85120	473	0.84880	1953	0.64	0.99120	321	0.91848	692	N.A.	
108	12.80	0.25	Deflag.	0.68314	9	0.66490	9	0.01	0.73896	485	0.74362	494	0.27	0.88003	309	0.80534	684	0.29	
122	13.10	0.13	No ign.																
115	14.10	0.25	Deflag.	N.A.	N.A.	N.A.	N.A.	N.A.	2.27800	265	2.26638	312	N.A.	2.59400	142	2.41277	300	N.A.	
121	14.20	0.13	No ign.																
102	14.29	0.50	No ign.																
120	15.00	0.13	No ign.																
114	15.00	0.25	No ign.																

Notes: Outcomes are no ignition, deflagration only, DDT events observed, or sustained detonation.

Flame arrival time occurs when the light sensor first detects light prior to full saturation.

Maximum pressure arrival time may lag first arrival of the pressure or shock wave.

Bold maximum pressure data indicates that a shock wave has formed with instantaneous rise time.

Red data is interpolated data from adjacent or nearby sensors.

N.A. indicates that data is not available due to sensor failure or a problem with the data acquisition system.

Velocity, both flame and pressure wave, is computed from a backward difference in arrival time.

points above the line and half below. Flame velocity is greater than 300 m/s over the composition range 6.1–14.1% NG–air, and reaches sonic velocity in the burned gases (800–1000 m/s) or more over the range 8.0–10.8% NG–air. Flame velocity is still increasing after passing 15 baffles over the range 6.2–12.8% NG–air. With more baffles and a longer tube, the flame velocity appears likely to reach sonic velocity over the entire flammable range of the test mixture.

The maximum pressure arrival time presented in Table 1 is found from observations of the first incoming pressure wave, which may or may not have developed into a shock wave with near instantaneous rise time. The time for this pressure wave to travel past the three baffles to the sensor at 5.94 m ranges from 0.148 to 1.305 s, depending on composition, and shows only a weak dependence on the blockage ratio. As with the flame arrival times, the pressure wave arrival time data is useful for model verification early in the flame development process.

Figure 7 shows the pressure wave velocity as a function of composition for all tests after passing various baffle sets and then exiting the tube. The four dashed lines are visual approximations of the pressure wave velocity data after passing 3, 7, 11, and 15 baffles. Similar to the flame velocity, the pressure wave velocity increases to more than 300 m/s over the composition range 6.1–14.1% NG–air, which is the same range that ignition was achieved. After passing 15 baffles, sonic velocity of 800–1000 m/s or more is achieved over the composition range 6.2–12.6%. Pressure wave acceleration shows a weak dependence on the blockage ratio with large BR leading to faster acceleration of the pressure wave. After passing 3 baffles, the pressure wave velocity ranges from about 10 to 50 m/s and shows no discernible dependence on BR. After passing

7 baffles, velocity ranges from 50 to 550 m/s for BR = 0.13 and from about 250 to 1000 m/s for BR = 0.25 and 0.50. After passing 11 baffles, velocity with BR = 0.13 lags velocity at BR = 0.25 and 0.50 by 200 m/s near the limits at 7% or 12% NG–air, but there is no difference in velocity as a function of BR for near-stoichiometric mixtures. After passing 15 baffles, the shock waves have all developed the same velocities with no discernible relationship to BR.

Figure 8 shows the maximum pressure as a function of composition for all tests. The four dashed lines are a visual approximation of the maximum observed pressure data after passing 3, 7, 11, and 15 baffles. Close examination of other data not presented here shows that BR has an effect on maximum pressure early in the flame acceleration process, but that effect is small later in the process after reaching 15 baffles. After passing 7 baffles, the sensor at 12.04 m recorded maximum pressure greater 1 MPa over a composition range from 8.0% to 11.3%. After passing 11 baffles at 18.14 m along the tube, maximum recorded pressure exceeded 1 MPa over the composition range 6.5–12.6%. After passing 15 baffles at 24.23 m along the tube, shock waves with near instantaneous rise time and magnitude ranging from 0.95 to 7.6 MPa were recorded over the composition range 6.5–12.4%, as indicated in Table 1. Maximum pressure within the baffled section of the tube as high as 7.6 MPa was observed for compositions ranging from 8.0% to 9.6%; however, these recorded pressures exceed the maximum range of the sensor which is 6.9 MPa.

Figure 9 shows typical pressure–time curves after the 15th baffle for compositions ranging from 6.5% to 12.4% NG–air. Maximum pressure greater than 0.8 MPa, the seal design pressure required by

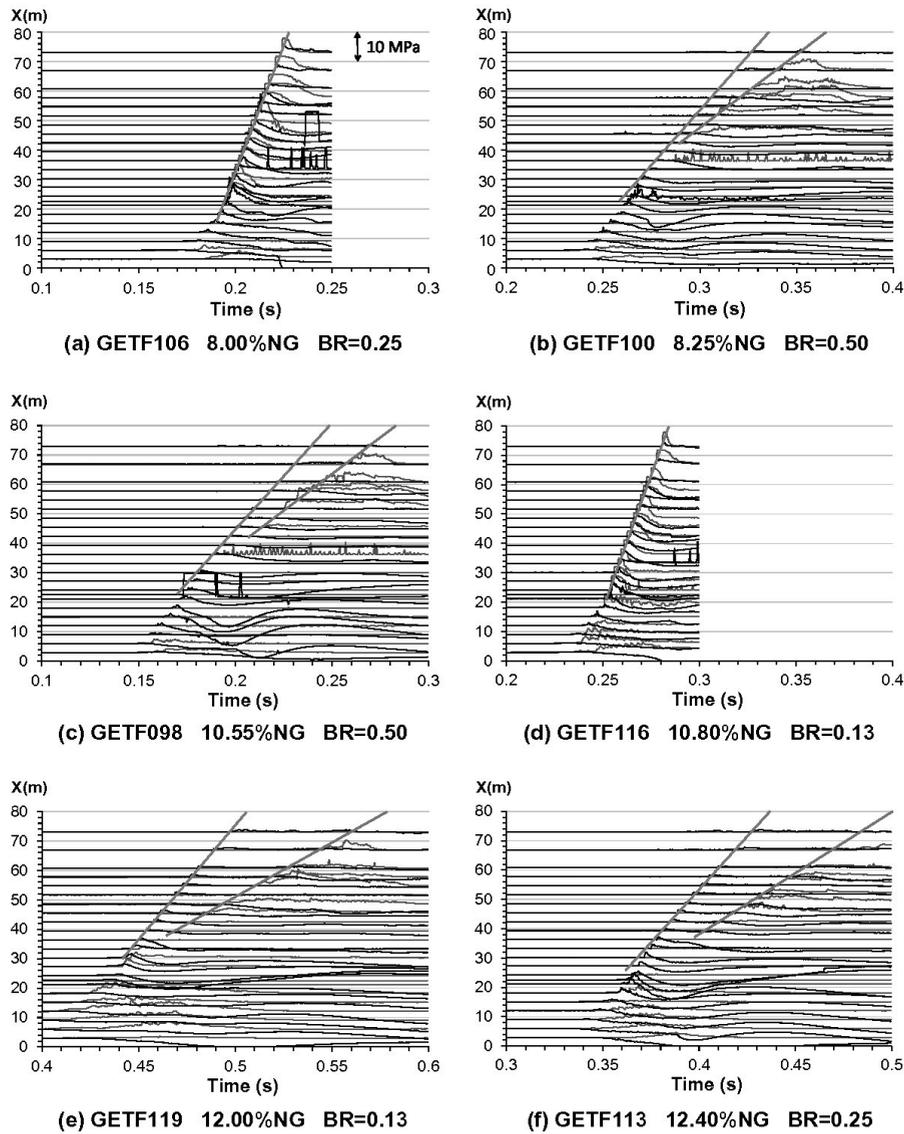


Fig. 5. The $x-t$ diagrams summarizing all pressure (black) and light (red) signals for 6 selected tests. Blue lines correspond to shock speed and green lines correspond to flame speed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

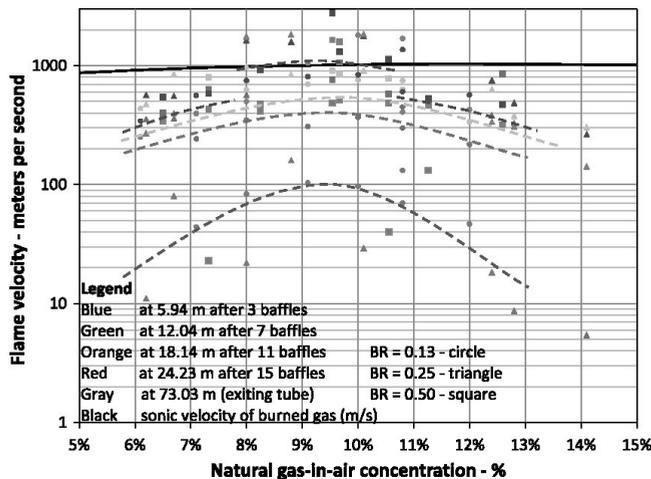


Fig. 6. Flame velocity for all tests.

coal mine safety regulations in the US, develops in all cases over this composition range. The green curve for Test 106 at 8.0% shows maximum pressure greater than 7.6 MPa which is more than the range for the pressure sensor. Close examination of the $x-t$ diagram for Test 106 in Fig. 5 shows that this high pressure is associated with the DDT event which occurred close to the pressure sensor around the 15th baffle at $x = 22.5$ m. Similarly, the yellow curve for Test 116 at 10.8% in Fig. 9 shows a high pressure of 4.2 MPa and is also associated with the DDT event as shown in Fig. 5. The black curve for Test 95 at 9.54% shown in Fig. 9 is typical of self-sustained detonation. In that test, the DDT event occurred well before the pressure sensor at the 15th baffle.

The proximity of the pressure sensor to the DDT event also affected the impulse or pressure-time integral associated with these curves. By inspection, the impulse associated with both the green and yellow¹ curves in Fig. 9 is greater than the impulse associated with the black curve. Again, the green and yellow curves were measured close to the DDT event where the detonation wave front could

¹ For interpretation of color in Figs. 9 and 12, the reader is referred to the web version of this article.

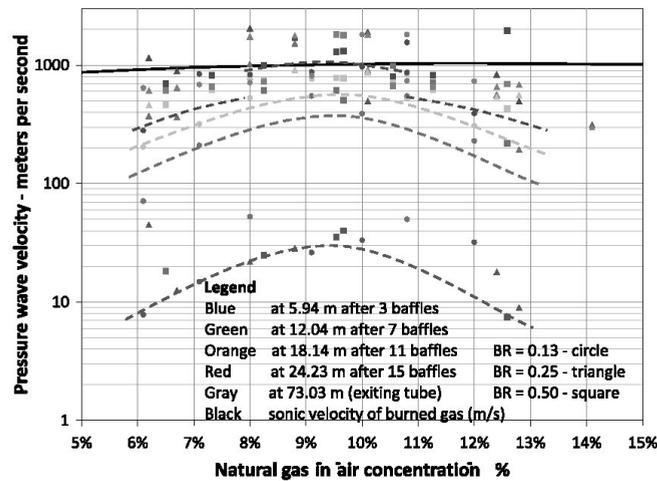


Fig. 7. Pressure wave velocity for all tests.

be propagating through pre-compressed NG–air mixture leading to higher measurements of both pressure and impulse.

5. Run-up distance to supersonic flame and ddt

As indicated in Table 1 and shown in Fig. 5, DDT was observed within the baffled section of the tube over compositions ranging from 8.0% to 10.8% NG–air, and in most cases, the DDT produced a sustained detonation beyond the baffles to the end of the tube in its smooth section. DDT is observed with all BR examined – 0.13, 0.25, and 0.50. Table 2 summarizes the tests in Table 1 that developed DDT or sustained detonation giving the observed run-up lengths to supersonic flame (X_{ru}) and DDT (X_{DDT}). The criteria for run-up length to supersonic flame are both shock and flame velocity are greater than 800 m/s and the shock pressure is greater than 1 MPa. The position of a DDT event is greater than or equal to X_{ru} and where the shock pressure exceeds 2 MPa. In most cases, the DDT event produced pressure exceeding about 4 MPa, and is easy to discern from the pressure–time data.

DDT events within the baffled section are characterized by shock velocities in the range of 1300–2000 m/s. Flame velocities in the baffled section associated with DDT also vary widely due to the difficulty of determining the exact “flame front” of the complex turbulent flame in the baffled section of the tube. However, those tests that produced a sustained detonation as observed near

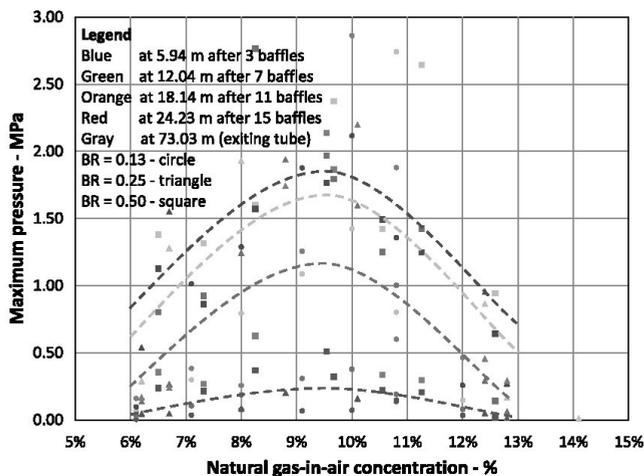


Fig. 8. Maximum observed pressure from all tests at various points along the GETF.

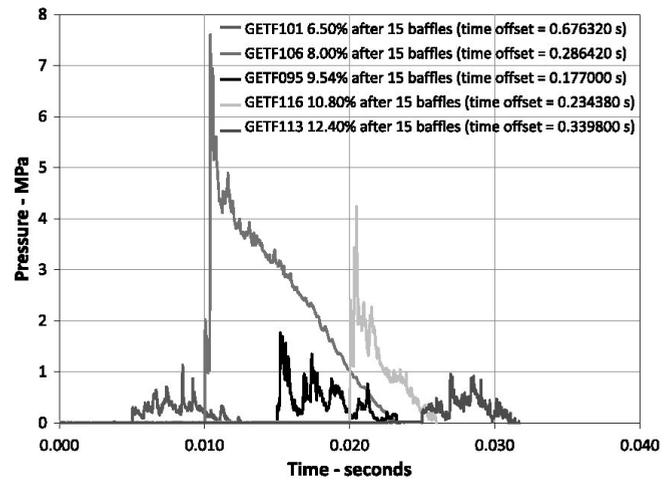


Fig. 9. Typical pressure–time curves for different test mixtures.

the end of the tube had shock and flame velocities of about 1700–1800 m/s with maximum pressure of about 1.7–3 MPa, consistent with expectations from CJ detonation theory.

Table 3 summarizes the distance to supersonic flame and DDT data from Table 2 in terms of the blockage ratio. The observed range of distance to supersonic flame and DDT is modified to reflect measurement error by subtracting or adding half the distance between sensors (1.5 m), and then normalizing by the tube diameter D (1.05 m). The flame reached supersonic velocity after passing as few as 7 baffles at a distance X_{ru} of 12 m corresponding to normalized distance (X_{ru}/D) of about 10. Location of the first DDT event was at baffle 11 at a distance X_{DDT} of 18 m and normalized distance (X_{DDT}/D) of 16.

Lines in Fig. 10 [15] show the combined empirical model for the run-up distance to sonic velocity as a function of BR for the stoichiometric methane–air mixture and $D = 1$ m. The ranges for run-up distance to supersonic flame and DDT from Table 3 are added at BR = 0.13, 0.25, and 0.50. Data from GETF experiments lies below the estimated relationship in the BR range 0.1–0.3, meaning that the flame accelerates faster than predicted; however, the data point at BR = 0.5 lies above the estimated relationship meaning that the flame accelerates slower than predicted. This data suggests that the distance to supersonic flame and DDT is independent of BR. One possible source of this discrepancy is the different obstruction geometry used in GETF experiments. Data for the empirical model came from experiments using concentric rings for baffles inside of explosion tubes, whereas GETF experiments used a steel beam placed across the tube. Another possible explanation is that the empirical models [15–17] do not apply to the BR range 0.1–0.3. The dashed line in Fig. 10 is an arbitrary “bridge” between two models and could be incorrect.

6. Comparison to flame acceleration and ddt criteria

Table 4 summarizes certain key data from these experiments and evaluates two DDT criteria – minimum tube diameter criterion and the minimum scale criterion. The effective diameter of the tube is the largest distance between the tube wall and the baffle (Fig. 3). The flange width for the W200x100 beams used for baffles is 21 cm. For BR = 0.25, the effective diameter, d , is half the tube width or 52 cm, and for BR = 0.50, d is 31 cm (52–21). For BR = 0.13, half the flange was cut from the beam, and d is 62 cm (52 + 10). The approximate detonation cell size, λ , is estimated from the NG–air composition using an empirical relationship determined in previous detonation studies [2,3], and ranges from

Table 2
Observed distance to supersonic flame (X_{ru}) and DDT (X_{DDT}).

GETF test #	NG-air (%)	BR	X_{ru} (m)	X_{DDT} (m)
106	8.00	0.25	21	22.5
100	8.25	0.50	21	22.5
105	8.80	0.25	18	18
127	9.10	0.13	22.5	22.5
95	9.54	0.50	18	18
96	9.67	0.50	18	21
117	10.00	0.13	18	21
104	10.10	0.25	12	18
98	10.55	0.50	15	18
116	10.80	0.13	18	22.5

Notes: X_{ru} is the run-up length to where shock velocity and flame velocity are greater than 800 m/s and shock pressure is greater than 1 MPa.

X_{DDT} is the likely location of DDT after reaching X_{ru} and where shock pressure exceeds 2 MPa.

27 cm for near-stoichiometric mixtures up to 200 cm nearer the flammable limits. The minimum scale length, L , to support detonation is calculated from Eq. (1), where D is the tube diameter (105 cm), S is the baffle spacing (152 cm), and d is the effective diameter as above.

Flame velocity is measured upon exiting the last set (15th) of baffles at a distance of 24.2 m from the ignition point. The first condition for DDT is sonic flame velocity. Flame velocities conducive to DDT (>800 m/s) are colored green, and those not conducive are red. The minimum tube diameter criterion ($d > \lambda$) and the minimum scale criterion ($L > 7\lambda$) are evaluated as yes or no. The uncertainty in the cell size estimates is about 30% [2,3], which will affect these criteria evaluations to some extent. If both criteria are not satisfied, the data in Table 4 are colored red; if one criterion is satisfied, the data are yellow, and if both criteria are met, the data are green, meaning that DDT and detonation is possible. Table 4 also provides actual test observations – 7 tests resulted in DDT and a sustained detonation beyond the last baffle and 3 tests developed DDT events within the baffled section of the tube, but the detonation was not sustained in the smooth section of the tube.

The minimum tube diameter criterion (d/λ) versus effective tube diameter, d , is plotted in Fig. 11. The 7 tests that resulted in a sustained detonation (green squares) have $d/\lambda > 1$ indicating good agreement with this criterion. In 3 tests (yellow dots), DDT is observed within the baffled section of the tube, but a sustained detonation did not develop. One of these tests with $d/\lambda = 0.69$ does not support the minimum tube diameter criterion. Of the remaining 14 tests that achieved ignition, 8 do not satisfy the criterion meaning that DDT is not possible (black crosses). However, 6 of the tests did satisfy the criterion meaning that DDT is possible (red diamonds). In these 6 tests, the flame had already accelerated to velocities of 500–800 m/s. With more baffles in the tube, it is likely that DDT and sustained detonation with this size tube could extend to the composition range 8.0–12.8% NG-air.

The minimum scale criterion (L/λ) versus length, L , is plotted in Fig. 12. In 3 of the observed sustained detonations (green squares), L/λ is less than 7, the accepted approximate value for this criterion. This data suggests that $L/\lambda > 5$ may fit observations better, though they are still within the 30% accuracy of the original $L/\lambda > 7$

Table 3
Analysis of distance to supersonic flame and DDT.

BR	Distance to supersonic flame – X_{ru}			Distance to DDT – X_{DDT}		
	Observed range (m)	Observed range with error (m)	Normalized range (X_{ru}/D)	Observed range (m)	Observed range with error (m)	Normalized range (X_{DDT}/D)
0.13	18–22.5	16.5–24	16–23	21–22.5	19.5–24	19–23
0.25	12–21	10.5–22.5	10–21	18–22.5	16.5–24	16–23
0.50	15–21	13.5–22.5	13–21	18–22.5	16.5–24	16–23

criterion [25]. There is also some uncertainty in the definition of L since Eq. (1) was derived for obstacle geometries different from those used in GETF experiments.

The minimum tube diameter (d/λ) and the minimum scale criteria (L/λ) impose limits on the composition range for possible DDT and sustained detonation that can be achieved with the GETF tube and its baffle system. At BR = 0.13 with an effective tube diameter of 62 cm, sustained detonation is only possible in this experimental apparatus over the composition range about 7.8–13.5%. At BR = 0.25 with an effective diameter of 50 cm, this range narrows to about 8.5–13.0%, and at BR = 0.50 with effective diameter of 31 cm, it narrows further to about 9.0–12.0%. The observed range for DDT and sustained detonation in these experiments is 8.0–10.8%. Increasing the number of baffles might expand the observed limits somewhat, but no more than the limitations of the experimental setup itself.

Figure 13 [27] shows regions for (1) slow, subsonic flames, (2) fast, sonic flames, and (3) DDT as a function of methane-air composition and tube diameter. This diagram reflects the minimum tube diameter criterion ($d > \lambda$) which states that the minimum tube diameter to support detonation must exceed the detonation cell size. For tube diameters of 300 mm, DDT and detonation can only develop for near stoichiometric mixtures of about 10% with $\lambda \approx 300$ mm. As the tube diameter increases, DDT and detonation become possible over an ever-widening composition range with larger detonation cell sizes. Kuznetsov et al. [27] hypothesized that DDT is possible over the range 6–16% methane-air for tubes with diameter greater than 1000 mm. Results from GETF experiments are indicated along a line at a tube diameter of 1050 mm on Fig. 13. Ignition with an electric match was achieved over the range 6.1–14.1%. Slow flames with velocity ranging from 300 to 800 m/s were observed at compositions ranging from 6.1% to 8.0% and

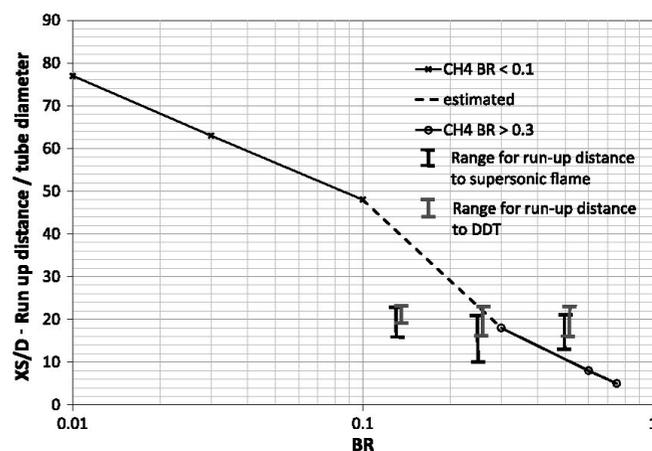


Fig. 10. Normalized run-up distance to sonic flame speed in the burned gases versus blockage ratio (after Ciccirelli and Dorofeev [15]). Observed range for run-up distance to supersonic flame (black) and DDT (red) from these tests added at BR = 0.13, 0.25, and 0.50. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
DDT criterion analysis.

GETF Test #	NG-air (%)	BR	Effective diameter d (cm)	Cell size λ (cm)	Length L (cm)	Flame velocity (m/s)	Min. dia. criterion $d > \lambda$?	Min. scale criterion $L > 7\lambda$?	Test outcome
123	5.10	0.13	62	200	314	0	no	no	No ign.
111	5.20	0.25	52	200	255	0	no	no	No ign.
124	6.10	0.13	62	180	314	343	no	no	Deflag.
112	6.20	0.25	52	160	255	565	no	no	Deflag.
101	6.50	0.50	31	125	182	543	no	no	Deflag.
107	6.70	0.25	52	110	255	556	no	no	Deflag.
125	7.10	0.13	62	80	314	561	no	no	Deflag.
97	7.32	0.50	31	70	182	583	no	no	Deflag.
126	8.00	0.13	62	50	314	750	yes	no	Deflag.
106	8.00	0.25	52	50	255	1640	yes	no	Sus. Det.
100	8.25	0.50	31	45	182	925	no	no	DDT
105	8.80	0.25	52	35	255	1589	yes	yes	Sus. Det.
127	9.10	0.13	62	32	314	812	yes	yes	DDT
95	9.54	0.50	31	30	182	2773	yes	no	Sus. Det.
96	9.67	0.50	31	28	182	1315	yes	no	Sus. Det.
117	10.00	0.13	62	27	314	839	yes	yes	Sus. Det.
104	10.10	0.25	52	27	255	1773	yes	yes	Sus. Det.
98	10.55	0.50	31	27	182	1135	yes	no	DDT
116	10.80	0.13	62	27	314	1365	yes	yes	Sus. Det.
118	10.80	0.13	62	27	314	604	yes	yes	Deflag.
99	11.26	0.50	31	30	182	530	yes	no	Deflag.
119	12.00	0.13	62	35	314	569	yes	yes	Deflag.
113	12.40	0.25	52	38	255	752	yes	no	Deflag.
103	12.59	0.50	31	41	182	473	no	no	Deflag.
108	12.80	0.25	52	45	255	485	yes	no	Deflag.
122	13.10	0.13	62	50	314	0	yes	no	No ign.
115	14.10	0.25	52	70	255	265	no	no	Deflag.
121	14.20	0.13	62	73	314	0	no	no	No ign.
102	14.29	0.50	31	74	182	0	no	no	No ign.
120	15.00	0.13	62	105	314	0	no	no	No ign.
114	15.00	0.25	52	105	255	0	no	no	No ign.

Note: Detonation cell size, λ , is estimated from an empirical correlation and can vary $\pm 30\%$.

10.8% to 14.1% NG-air. Fast flames with velocity ranging from 800 to 1000 m/s were observed at compositions ranging from 8.0% to 10.8% NG-air. DDT with sustained detonation developed over this same range. These ranges are less than those hypothesized by Kuznetsov et al. [27]. As mentioned earlier, the number of baffle sets in these experiments was limited to 15, but with more baffles and greater length of tube to accelerate the flame, the composition

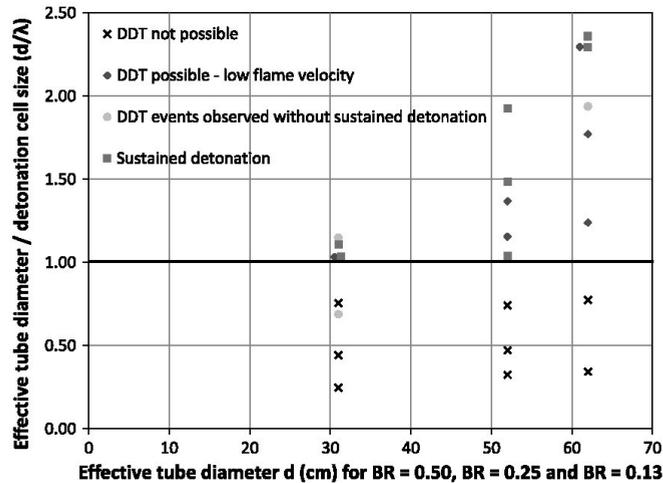


Fig. 11. Minimum tube diameter criterion for DDT ($d > \lambda$) showing tests where DDT and sustained detonation developed.

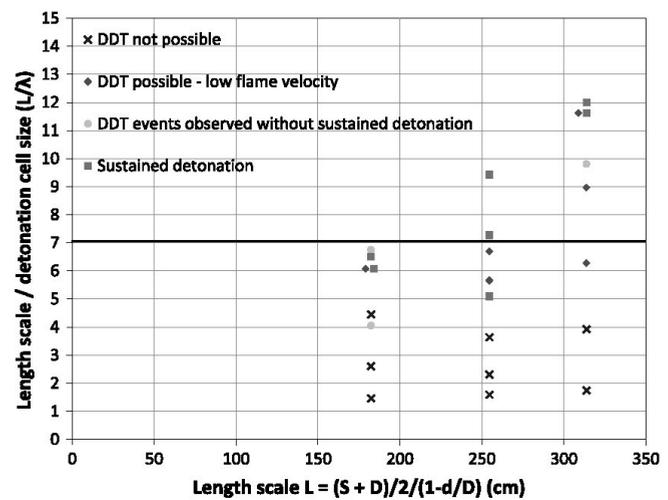


Fig. 12. Minimum scale criterion for DDT ($L > 7\lambda$) showing tests where DDT and sustained detonation developed.

range for DDT and detonation can only increase, up to the limitations of the experimental setup itself.

7. Summary

We conducted a series of large-scale experiments aimed to answer several critical questions relevant to underground coal mine

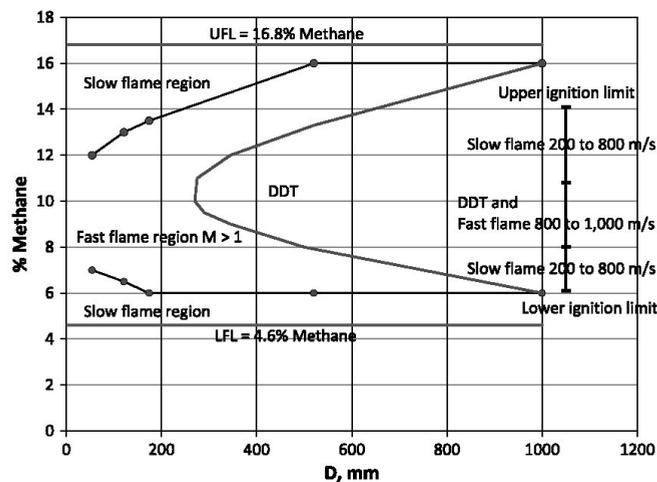


Fig. 13. Slow flame, fast flame, and DDT limits as function of composition and tube diameter at normal conditions $p = 1$ bar and $T = 293$ K (after Kuznetsov et al. [27]). Natural gas-air data from these tests added at $D = 1050$ mm.

safety – (1) can weak spark ignition of NG-air mixtures develop into detonation, (2) what physical conditions contribute to flame acceleration and possible DDT, and (3) what explosion pressures can develop? The experiments demonstrate that weak spark ignition of NG-air mixtures can develop into a detonation. Ignition with a weak spark from an electric match was achieved over the composition range 6.1–14.1% NG-air. The flame and pressure wave velocity reached at least 300 m/s over this entire composition range after passing the last (15th) baffle. Flame velocity was increasing at the last baffle over the range 6.2–12.8% NG-air and reached sonic velocity in the burned gases (800–1000 m/s) over the range 8.0–10.8% NG-air. Pressure wave velocity was increasing over the range 6.1–14.1% NG-air and reached sonic velocity over the range 6.2–12.6% NG-air. As shown in Fig. 5, DDT and sustained detonation in the smooth part of the tube was observed over the composition range 8.0–10.8% NG-air. After passing 15 baffles, shock waves with magnitude greater than 1 MPa were measured in all tests over the composition range 6.5–12.4%. Shock waves with magnitude ranging from 3 to 7.6 MPa (at the upper limit of the pressure measuring sensors) were observed in 5 tests with composition ranging from 8% to 11%. The observed range for DDT and sustained detonation could be extended somewhat with the addition of more turbulence-generating obstacles and length of flammable mixture. However, that range is limited by the size characteristics of the GETF itself, and it is not likely to be extended beyond about 7.8–13.5% NG-air using this experimental apparatus.

The observed run-up length to sonic flame velocity normalized by the tube diameter, X_{ru}/D , ranges from 16 to 23 at $BR = 0.13$, 10 to 21 for $BR = 0.25$, and 13 to 21 for $BR = 0.50$. The observed run-up length to DDT normalized by the tube diameter, X_{DDT}/D , ranges from 19 to 23 at $BR = 0.13$, and 16 to 23 for $BR = 0.25$ and 0.50.

The run-up distance to sonic flame velocity, X_{ru} , is less than that expected based on empirical models (Fig. 10); however, that difference may be due to the different baffle geometry used in these experiments. Blockage ratio affects the flame acceleration, but the effect is not strong in these experiments. More sets of baffles or obstacles in a longer tube can only promote flame acceleration to sonic velocity over a wider composition range.

Data from these experiments supports the minimum tube diameter criterion ($d/\lambda > 1$) for possible DDT and sustained detonation. The data also supports the minimum scale criterion ($L/\lambda > 7$); however, the threshold value of L/λ for DDT and sustained detonation may be as low as 5. For a 1-m-diameter tube, Kuznetsov et al. [27] suggest that DDT and sustained detonation in NG-air

mixtures could occur over the composition range 6–16%, whereas, these experiments only found it over 8.0–10.8%. This difference is related to the baffle arrangement that reduces the effective diameter of the GETF, as well as to the limited tube length and the limited number of baffles. The 73-m-long tube used in these experiments contained 15 sets of baffles in the first 23.6 m of its length. As with flame acceleration, more sets of baffles or obstructions in a longer tube can only promote DDT and sustained detonation over a wider composition range, but only up to the limitations of the experimental setup itself.

Current coal mine safety regulations require coal mine seals to resist an explosion pressure-time curve that rises instantaneously to 0.8 MPa and remains there for 4 s. Measured pressure-time curves observed during the course of these experiments demonstrate that maximum explosion pressure can exceed this statutory requirement. The duration of the pressure above this limit in these experiments is less than about 10 ms, and it is related to the length of the explosion tube and the pressure wave velocity. Because the tube used in these experiments is open ended, the burned gases vent to the atmosphere immediately, and the pressure duration is small. An explosion within the sealed area of a coal mine is not vented, and the explosion pressure equilibrates to the constant-volume explosion pressure until the burned gases cool or escape through other means.

Tunnels in US coal mines typically have a rectangular profile about 6-m-wide by 2-m-high and a typical effective diameter (D) of about 2 m. Three or more main tunnels can run in parallel for several kilometers, and they are connected every 30–60 m with perpendicular crosscuts. The tunnels will almost always have numerous obstacles along their entire length, such as mining equipment, piles of waste rock, and roof supports (cribs and posts), which all impede airflow and generate turbulence. The obstacles inside typical coal mine tunnels function similarly to the baffles inside the explosion tube used in these experiments (Fig. 3).

To achieve DDT and sustained detonation of a flammable mixture in a coal mine tunnel, flame should first accelerate to sonic velocity in the burned gases. The normalized run-up distance, X_{ru}/D , required to accelerate a flame to sonic velocity in a 1-m-diameter tube ranges from as low as 20 for near stoichiometric mixtures with $BR = 0.25$ –0.50, to 75 or more in smooth tubes with $BR = 0.01$, assuming that the empirical models for flame acceleration shown in Fig. 10 apply. Since X_{ru}/D decreases with increasing D , the distance required to achieve sonic flame velocity in a typical coal mine tunnel with $D = 2$ m might range from less than 40 m for near stoichiometric mixtures in a highly obstructed tunnel to less than 150 m in a smooth tunnel. If the length of flammable mixture exceeds these lengths in a coal mine tunnel, accelerating the flame to sonic velocity could occur. Once sufficient flame velocity develops, two necessary criteria may apply for the onset of DDT. The minimum tube diameter criterion ($d > \lambda$) is met in most cases, since the typical effective diameter, D , for a coal mine tunnel is about 2 m, and the maximum detonation cell size, λ , at the flammable limits is also about 2 m. For heavily obstructed channels ($BR > 0.1$), the minimum scale criterion ($L > 7\lambda$) based on Eq. (1) may also apply. Thus, all the conditions for DDT and sustained detonation in coal mine tunnels can be met, and the possibility of detonation of NG-air mixtures in coal mine tunnels exists, if a flammable mixture of sufficient length forms.

However, the risk of developing a flammable mixture of sufficient size in a coal mine is not known and not well understood. The variable composition of the atmosphere within the sealed area of a coal mine affects its sensitivity to detonation. For example, the presence of ethane tends to enhance detonation sensitivity whereas the presence of carbon dioxide tends to suppress it. Maintaining a properly functioning ventilation system to ensure that flammable mixtures do not develop, monitoring the atmosphere

everywhere to detect such mixtures as they might develop, and controlling potential ignition sources are essential actions to follow at all times to decrease the risk associated with the low-probability, high-consequence event of a gas explosion in a coal mine.

Afterword

The gas explosion test facility (GETF) used in this research has been dismantled and is no longer available due to permanent closure of the NIOSH Lake Lynn Laboratory in 2012.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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