# Shock-induced void collapse mechanisms in detonation initiation

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#### 1. Introduction

The generation and merging of hotspots, or regions of localized energy release, are crucial processes in shock initiation of energetic materials. Hot spots may be formed due to shock interaction with inhomogeneities in energetic materials and propellants, including voids or pores in and between the constituent materials. Aging, thermal damage, and mechanical damage potentially change the structure and therefore the initiation characteristics of the material, affecting both ignition performance and safe handling, and necessitate modeling of material structure in predictive capabilities for shock initiation. The problem is complex, involving a large spectrum of length and time scales, thermal and mechanical fluid-structure coupling, and multi-species chemical kinetics.

Shock interaction with micro- and molecular-scale material heterogeneities through processes such as void collapse, shear banding, debonding, and micro-cracking may result in hotspots. Viscoplastic deformation and jetting have been identified as important processes for energy localization by shock-induced void collapse, although there is evidence that different processes dominate at different length scales. Because of the extreme range of scales involved, mesoscale codes are being developed to bridge between continuum and atomistic scales [1,2]. Data on the fundamental mechanisms involved in hot spot formation are required to assist in developing models for these codes.

Previous research has shown that the sensitivity of an energetic material to shock initiation is substantially increased by the presence of voids [3-5]. Shock-induced void collapse is one mechanism for hot spot formation and detonation initiation on the  $\mu$ m to mm scale, as illustrated by a recent corner-turning study in PBX-9502 by Ferm et al. (2002) [6] using proton radiography. Decoupling of the lead shock and reaction may occur upon diffraction around a corner creating so called dead zones of preshocked but unreacted material. Shock desensitization is suggested as a possible mechanism. Desensitization of heterogeneous energetic materials by a low-amplitude shock has been encountered in many applications, such as rock blasting [7] and munitions destruction [8]. Campbell and Travis (1985) [9] showed that the weak pre-shock collapses the voids in PBX-9404, rendering it insensitive to detonation. Recent double shock experiments by Salisbury et al. (2002) [10] examined the relative roles of "homogeneous" and "heterogeneous" components in detonation initiation and propagation in EDC37 and PBX-9501.

Numerous studies have investigated the symmetric collapse of voids or bubbles liquid/gas systems. In the presence of a shock, highly asymmetric collapse is possible. The shock accelerates the upstream interface of the pore, creating a high speed liquid jet between two

lobes of high temperature gas [11]. The high impact pressure on the upstream surface creates a potential initiation site in the material [12]. To predict the critical condition for initiation, it is necessary to know the interface velocity, temperature and pressure history resulting from the complex processes occurring during pore collapse. The current work contributes measurements of the interface location and velocity field during the stages of collapse with temporally and spatially resolved experimentation in a model hydrodynamic problem. We particularly focus on the mesoscale modeling problem of shock interaction with an array of voids.

## 2. Experimental Setup

The experiment used a single stage gas gun with a barrel length of 2.1m and a honed 51mm inner diameter, Fig.1. The material sample for this model two-dimensional hydrodynamic experiment is composed of a 1.6mm sheet of gel made from agarose and glycerol gradient buffer (GGB) cured directly into a PMMA mold. The voids are stamped into the gel after the curing process. The hardened steel slug flyer plate strikes an aluminum striker that protrudes 2cm from the mold and is mated to the gel sample. The flyer plate transmits a shock into the aluminum striker and from there into the gel. This arrangement prevents optical obscuring of the event due to shock loading of the PMMA mold enclosing the gel.



Figure 1. a) Gas gun facility and b) schematic of gas gun and test section.

Near the end of the gun barrel, two sets of infrared emitters and detectors measure the flyer plate velocity. Another emitter/detector pair is placed on the mounting rails as a triggering device for the diagnostics which include high speed shadowgraph imaging and particle image velocimetry (PIV) measurements of the velocity field. A rotating mirror camera (interframe time 2.5 µs, exposure 150 ns) with an 80 frame capacity per experiment using two rolls of 35 mm T-max 400 film is used for high speed shadowgraph imaging. Light from a 2 watt 532 nm laser was passed through an acousto-optic modulator that acts as a high speed shutter before being collimated to a 20 mm diameter beam to illuminate the experiment. Hollow glass particles of appoximately 50µm diameter are cured in the gel for the PIV measurements. A two-color, single-frame PIV system is used to take two-dimensional snapshots of the velocity field at different stages of the void collapse.

## 3. Results: Collapse of a single void

A single 2.5mm diameter cylindrical void set into an agarose-GGB gel was subjected to shock loading of different velocities introduced from a flyer plate. The shock causes the void to undergo an asymmetric collapse. The portion of the void impacted by the shock is driven inwards with the center portion moving faster than the material to the sides, resulting in a jet that impinges on the downstream interface[13]. The void collapses to about 1/5 of its initial volume, and then the void re-expands and an outwardly propagating rebound shock wave is observed in the shadowgraph images.

### 4. Results: Collapse of a void array

The collapse of a streamwise pair of voids subjected to a  $1562\pm7$ m/s initial shock was examined using high speed shadowgraph imaging. An x-t diagram of the void interface location measurements for the upstream (void1) and downstream (void2) voids is shown in Fig 2. The upstream void undergoes collapse similarly to the single void collapse discussed above. The collapse of the downstream void is delayed by the presence of the upstream void. Based on the single void data, collapse of the downstream void is expected to begin about 7.5µs after shock passage, so the additional delay of 15µs is due to shielding by the upstream void. The trigger for collapse of the downstream void appears to be the rebound shock emitted from the upstream void collapse. PIV measurements at selected times during the array collapse are shown in Fig 3 (shock propagated left to right).



Figure 3. PIV images during the collapse of a streamwise void array a) 47.5µs after shock:collapse and jetting of upstream void b) 27.5µs after shock: collapse and jetting of downstream void, upstream void rebound c) 55µs after shock: downstream void rebound.

<sup>21</sup>st ICDERS - July 23-27, 2007 - Poitiers

Staggered and aligned four-void arrays were subjected to shocks with pressure ratio of 260. PIV data during the collapse after shock passage are shown in Fig 4.



Figure 4. a) PIV images during collapse of a) a staggered array of 2.5mm voids b) an aligned array of 2.5mm voids.

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