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Title: Violent Reactions and DDT in Hot, Thermally Damaged HMX-Based PBXs

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Violent Reactions and DDT in Hot, Thermally Damaged HMX-Based PBXs

Gary Parker, **Matt Holmes**, Peter Dickson,
Blaine Asay & John McAfee

Group: WX-6, LANL

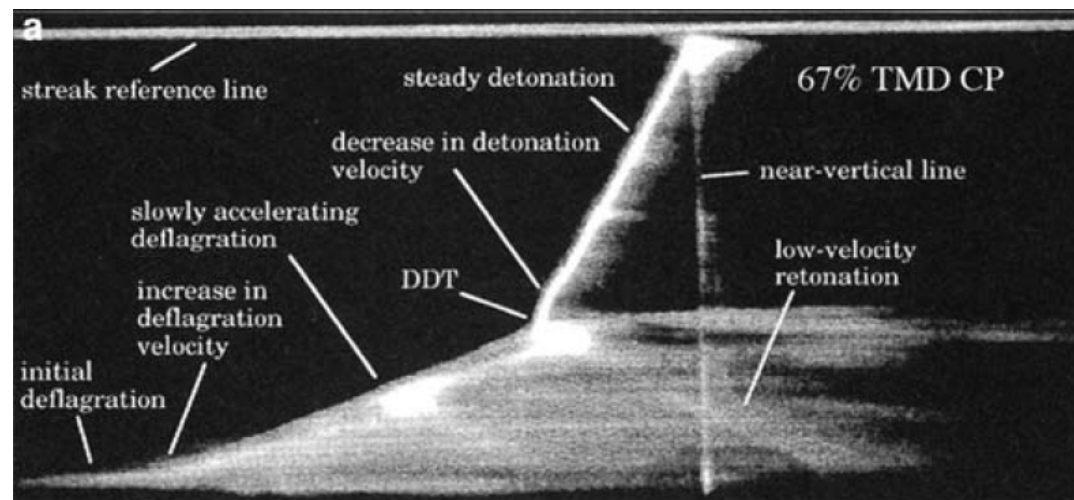
gparker@lanl.gov

Why Study HE in Abnormal Thermal Environments?

- Conventional high explosives (e.g. PBX 9501, LX-07) have been observed to react violently following thermal insult
 - Fast convective and compressive burns (HEVR)
 - Thermal explosions (HEVR)
 - Deflagration-to-detonation transition (DDT)
- No models exist that sufficiently capture/predict these complex multiphase and multiscale behaviors
- For now, research is focused on identifying vulnerabilities and factors that control this behavior

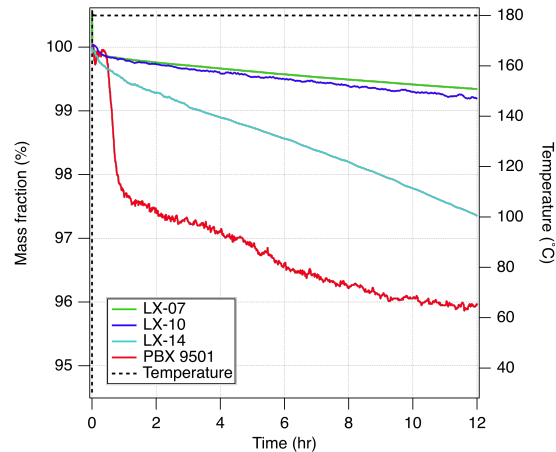
Background – Classic DDT Research

- DDT research performed with **low density granular beds at room temperature**
- DDT tube design imposes 1-dimensional reaction progression
- Often employed streak imaging (x-t diagrams)
- Useful for explaining DDT mechanics
- **Do these classic experiments represent realistic situations involving hot, high density, consolidated formulations?**

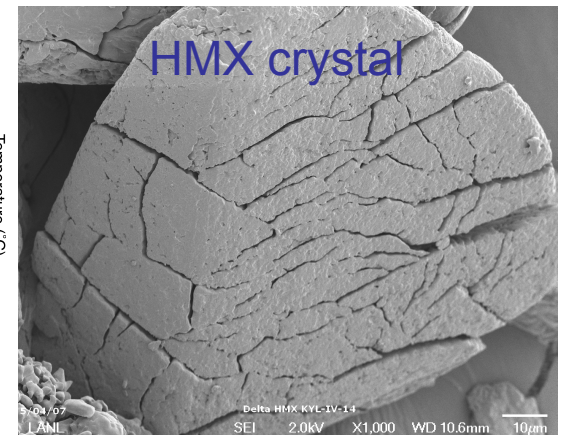


(Luebcke et al.)

Thermal Damage – HMX-Based PBXs



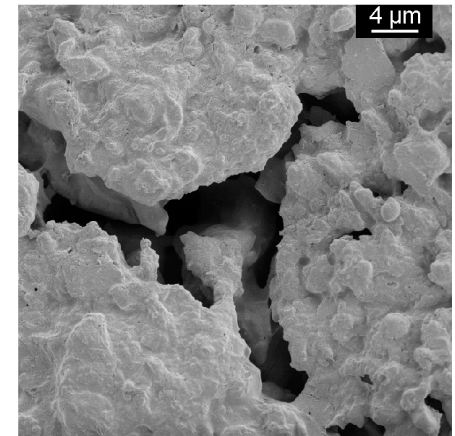
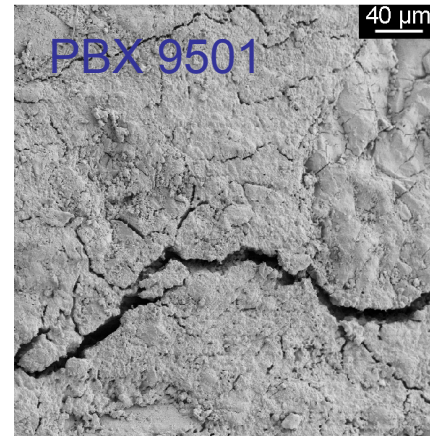
(Smilowitz)



(Roemer)

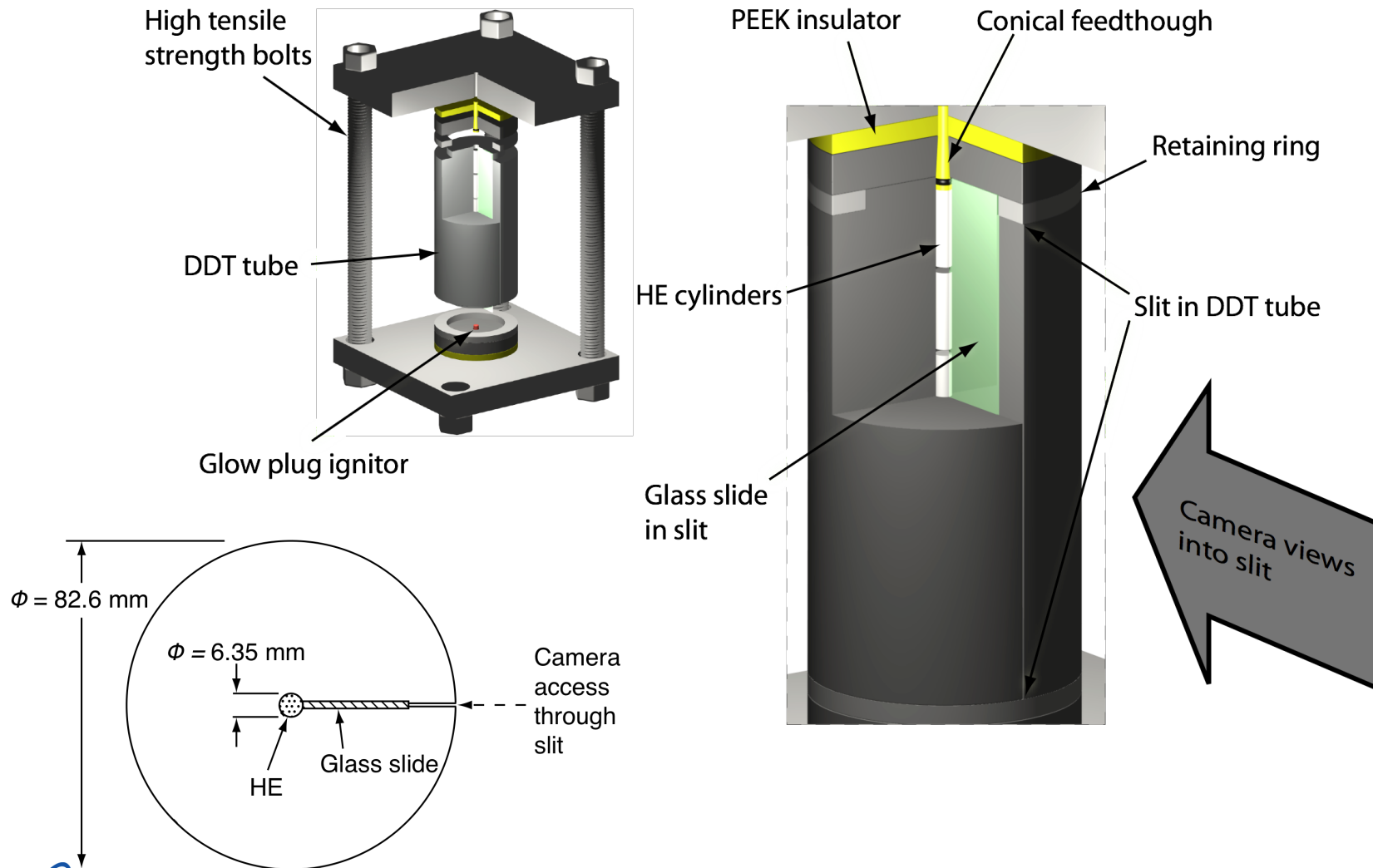
- Cracks form
- Decomposition/gasification = mass loss
- HMX phase transition fractures crystals
- Binder softens
- Interconnected porosity increases

Is the damage extensive enough to make these materials susceptible to DDT?

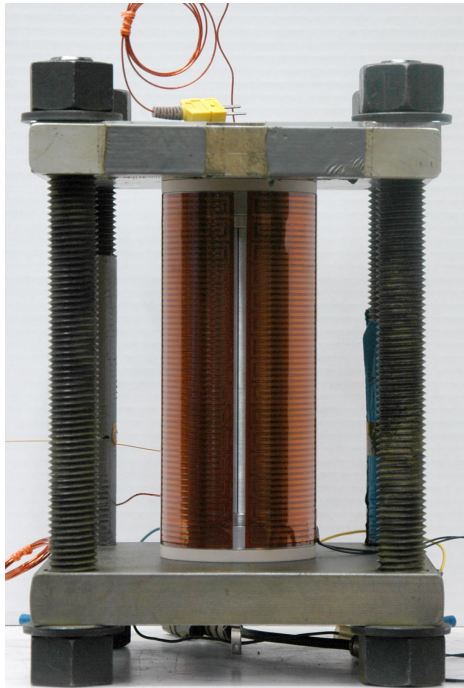


(Roemer)

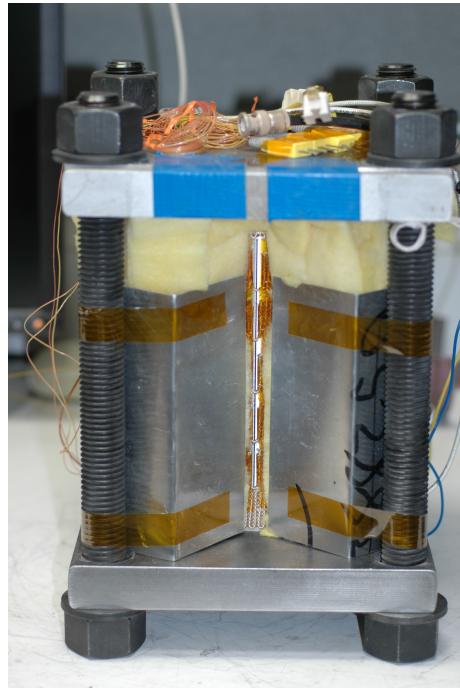
1D Hot DDT Tube Experiment - design



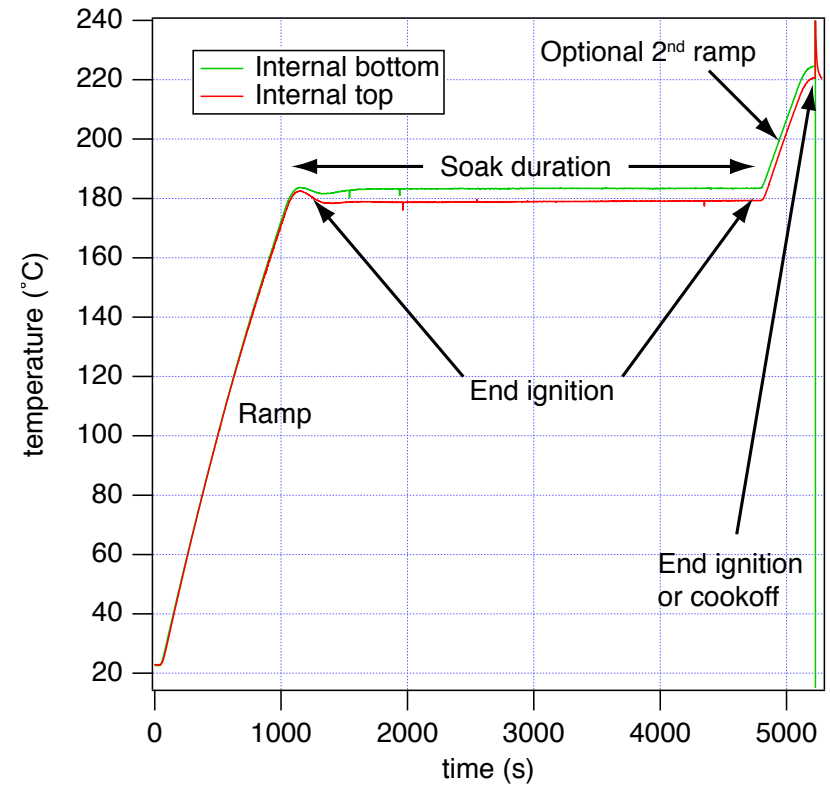
1D Hot DDT Tube Experiment - heating



DDT tube with flexible heater adhered to surface



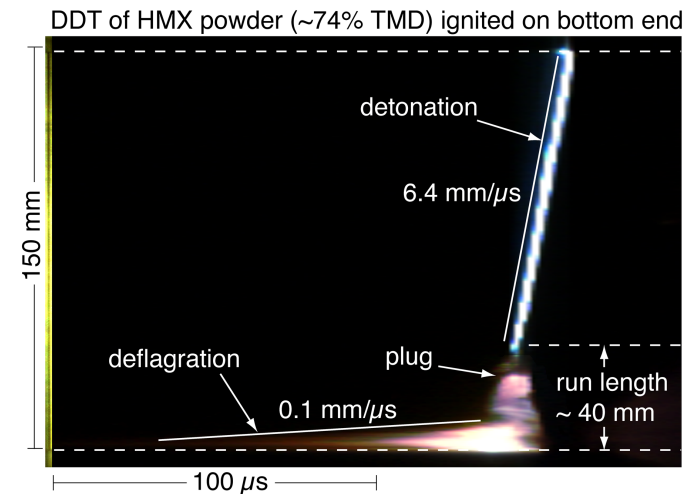
Full assembly wrapped in insulation



1D Hot DDT Tube Experiment - diagnostics

Streak imaging

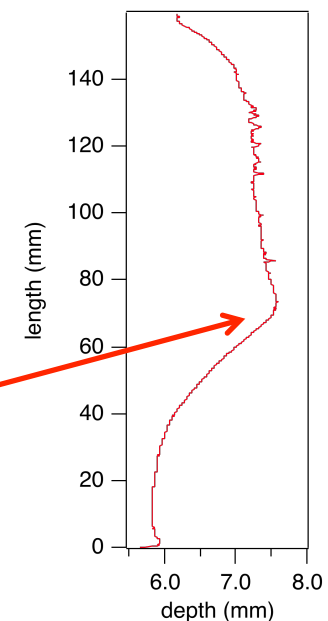
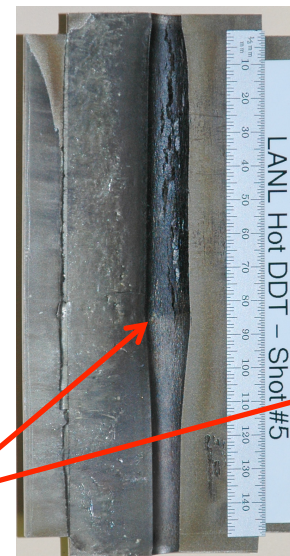
- Reaction velocity
- Burn mode characteristics
- DDT run length



Post-mortem case examination

- Change in surface characteristics (darkening in detonation zone)
- DDT run length
- Degree of deformation (dent depth)
- Work done by HE reaction

Transition point

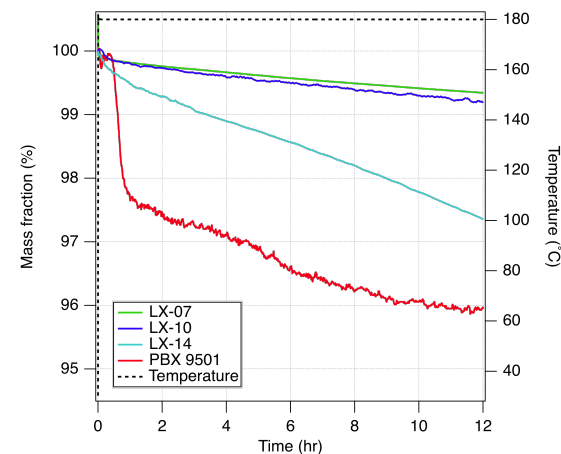


Test plan – Explosives tested

The plan was to compare four HMX-based PBX formulations to tease out the effects of the binder mass fraction and binder type following thermal damage

- BDNPA-F plasticizer is known to decompose/volatilize at $\sim 120^{\circ}\text{C}$
- Estane melts at $\sim 150^{\circ}\text{C}$
- Viton A is thermally stable and does not melt at the temperatures in this study

	HMX fill fraction (% by mass)	Binder fill fraction (% by mass)	Binder type
PBX 9501	95	5	50% Estane + 50% BDNPA-F plasticizer
LX-14	95.5	4.5	Estane
LX-10	94.5	5.5	Viton A
LX-07	90	10	Viton A

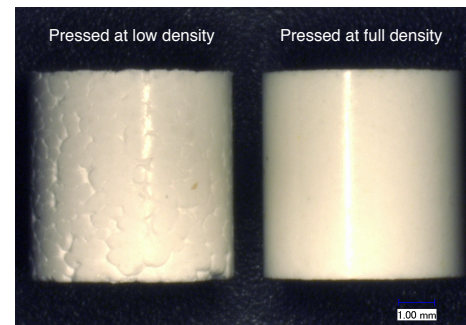
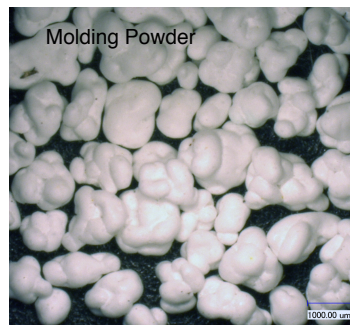


Test plan – Controlling void fraction

Void fraction would be varied by:

- Starting with low density pressings
- Soaking at elevated temperature to permit decomposition and mass loss

Void Fraction Bins					
Initial density	~70% TMD	~85% TMD	~93% TMD	~97% TMD	~98.5% TMD
Target initial void fraction	~30%	~15%	~7%	~3%	~1.5%
Loading method	Hand tamped molding prills	low ρ pressed cylinders	low ρ pressed cylinders	full ρ pressed cylinders	full ρ pressed cylinders
Thermal treatment	1 hr soak at 185°C	1 hr soak at 185°C	1 hr soak at 185°C	3 hr soak at 185°C	No soak, ramp until cookoff
Estimated void fraction at ignition	20-35%	12-16%	4-6%	0.5-3%	0-.0.5%



Hypotheses tested and why

Void fraction effects:

- Increased porosity → increased propensity for DDT & shorter run length
Classic DDT research has indicated a monotonic, inverse relationship exists between porosity and run length

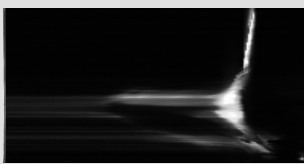
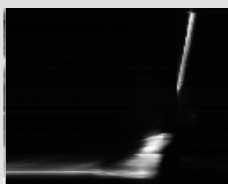
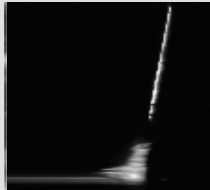
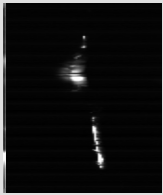
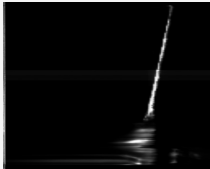
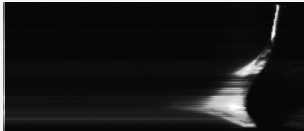
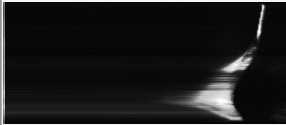
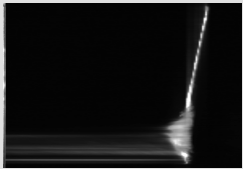
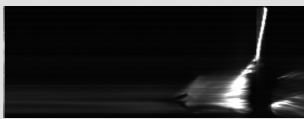
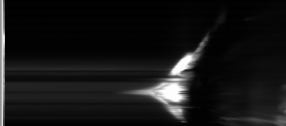
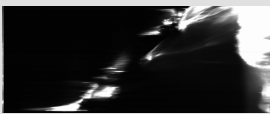
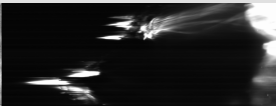
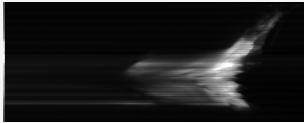
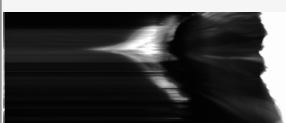
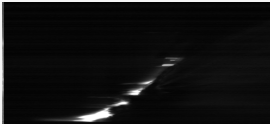
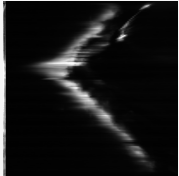
Binder system effects:

- Greater compliance of binder → increased propensity for DDT & shorter run length
- Higher HMX:binder fill fraction → increased propensity for DDT & shorter run length
Previous work with PBX 9501 in this experimental series indicated that a compression burn process played an important role in build-up to DDT

Cookoff effects:

- Thermal runaway to auto-ignition → increased propensity for DDT & shorter run length
Previous work with PBX 9501 in this experimental series indicated that the factors that contribute to DDT were exacerbated in the thermal runaway leading up to ignition

The Dataset

Void fraction at ignition	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501					
LX-14					No streak
LX-10					
LX-07					

Results

Void fraction at ignition	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

Results – How binder affects propensity for DDT

PBX 9501 vs. LX-14

Similarities:

Binder mass fraction &
Estane binder

Difference:

PBX 9501's binder is plasticized with BDNPA-F which makes it more compliant, but also gasifies readily at elevated temperature leading to more porosity formation

Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

Trends:

- More compliant binder → Increased DDT propensity
- More porosity → Increased DDT propensity

Results – How binder affects propensity for DDT

LX-14 vs. LX-10

Similarity:

Binder mass fraction

Difference:

LX-14 has an Estane binder which melts at ~150°C,

LX-10 has a Viton A binder which is thermally stable and does not melt

Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

Trends:

- More compliant binder → Increased DDT propensity
- More porosity → Increased DDT propensity

Results – How binder affects propensity for DDT

LX-10 vs. LX-14

Similarity:

Viton A binder

Difference:

LX-10 has 5.5% binder by mass,
LX-07 has 10% binder by mass

Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

Trends:

- Higher binder mass fraction → lower DDT propensity
- More porosity → Increased DDT propensity

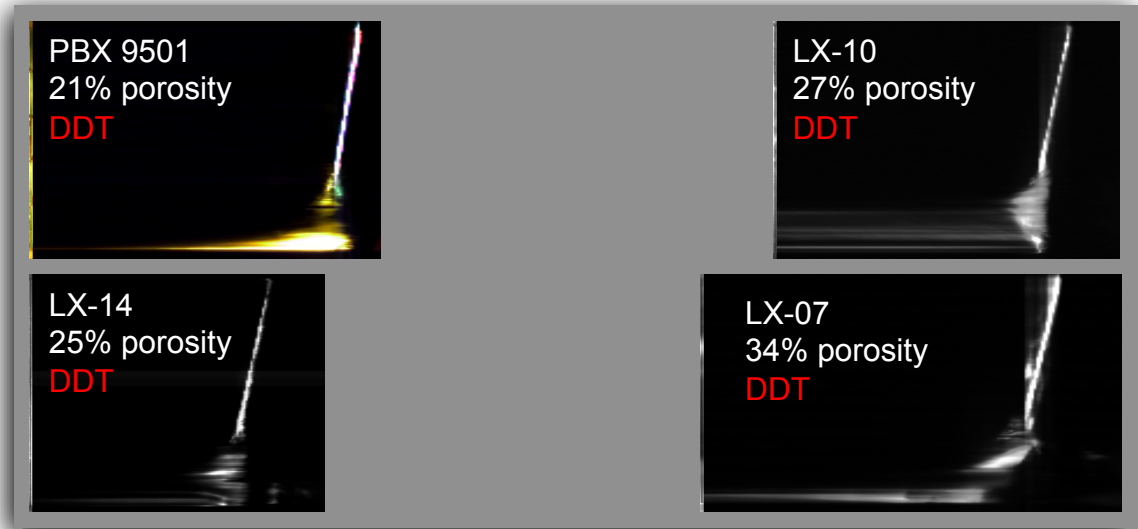
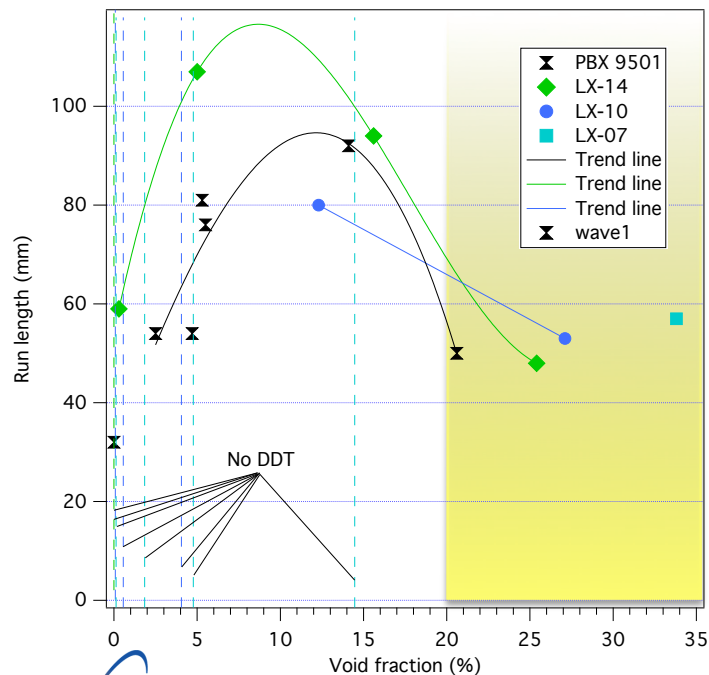
Results – How binder affects DDT run length

HE treatment:

Hand tamped molding prills, soaked for 1 hr, end-ignited

Observations:

- With high void fraction all four formulations DDT
- Similar features in images
- Similar run lengths within this void fraction bin



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

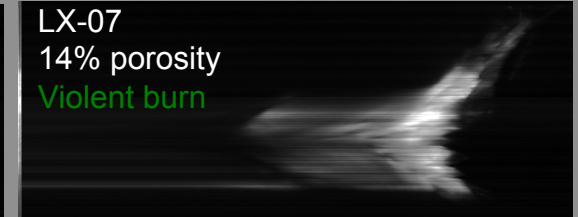
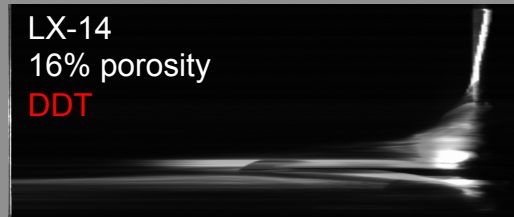
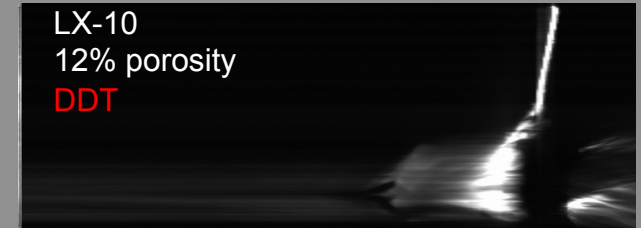
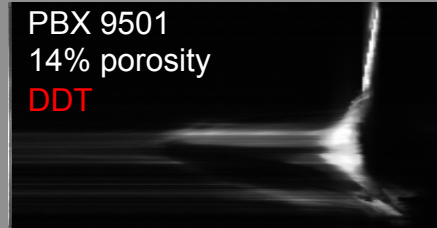
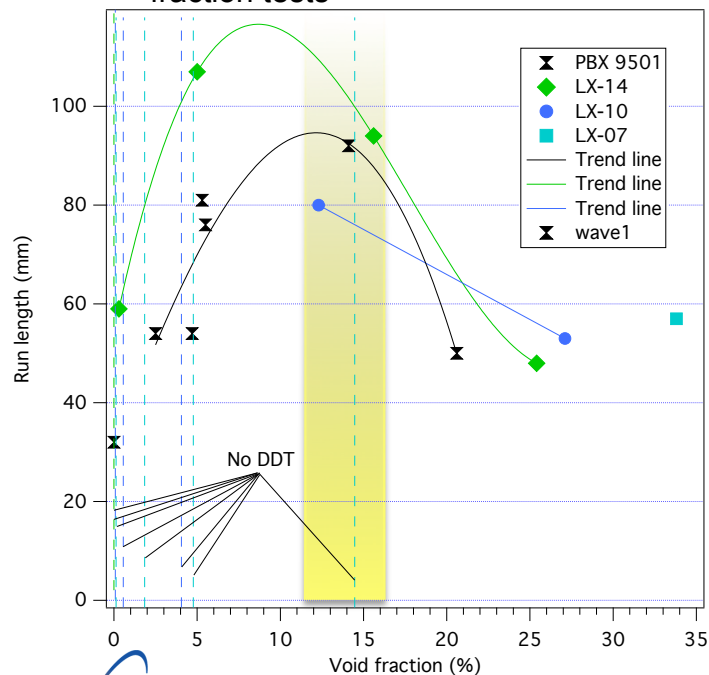
Results – How binder affects DDT run length

HE treatment:

Low ρ pressed cylinders, soaked for 1 hr, end-ignited

Observations:

- Substantial burning and thermal explosion before DDT
- Similar run lengths within this void fraction bin
- Longer run lengths than higher void fraction tests



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

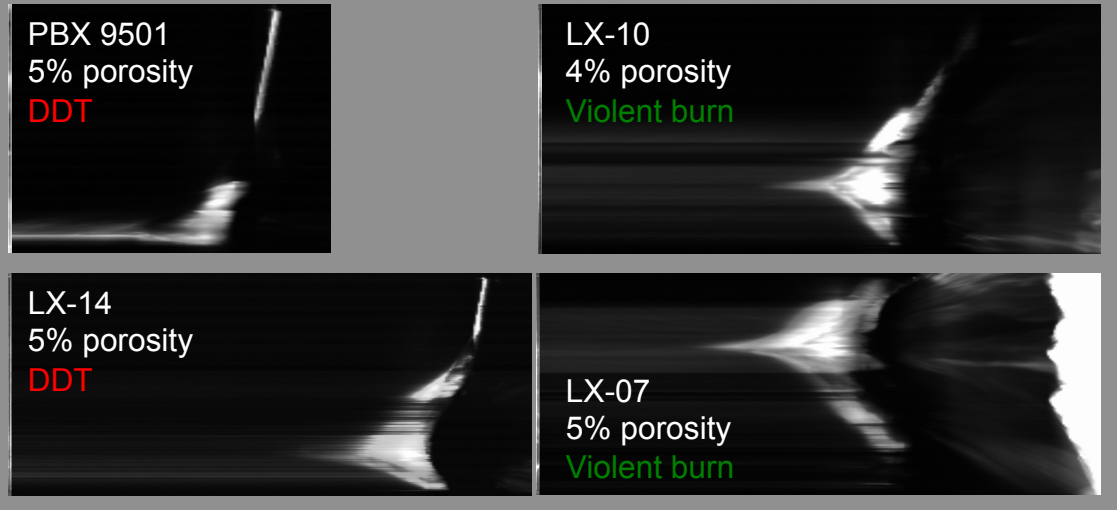
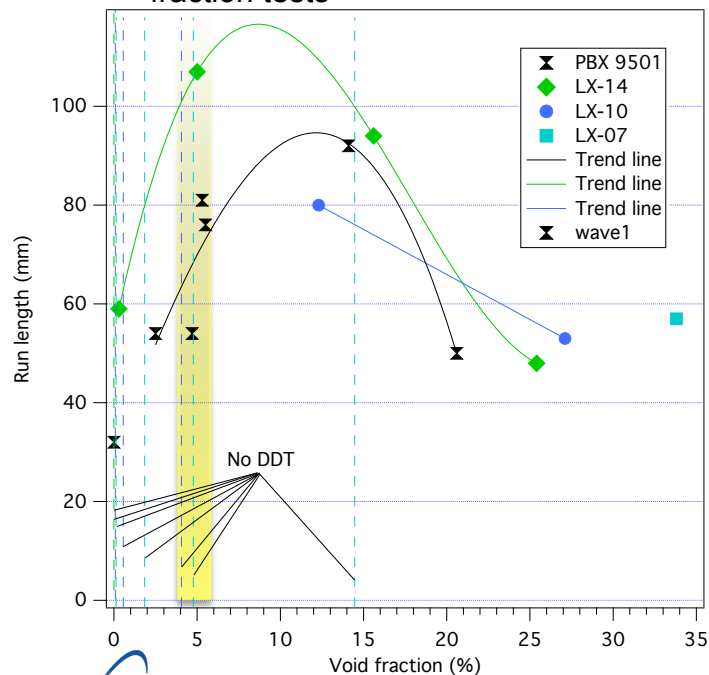
Results – How binder affects DDT run length

HE treatment:

Low ρ pressed cylinders, soaked for 1 hr, end-ignited

Observations:

- Thermal explosion location is different from shot to shot
- Do LX-10 and LX-07 need a longer run length than our tube to undergo DDT?
- Longer run lengths than highest void fraction tests



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

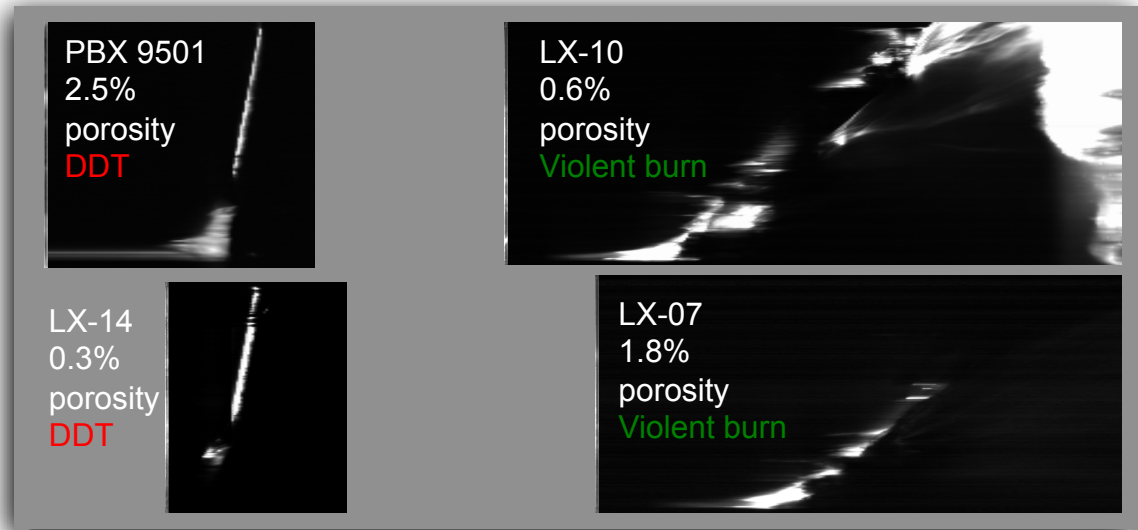
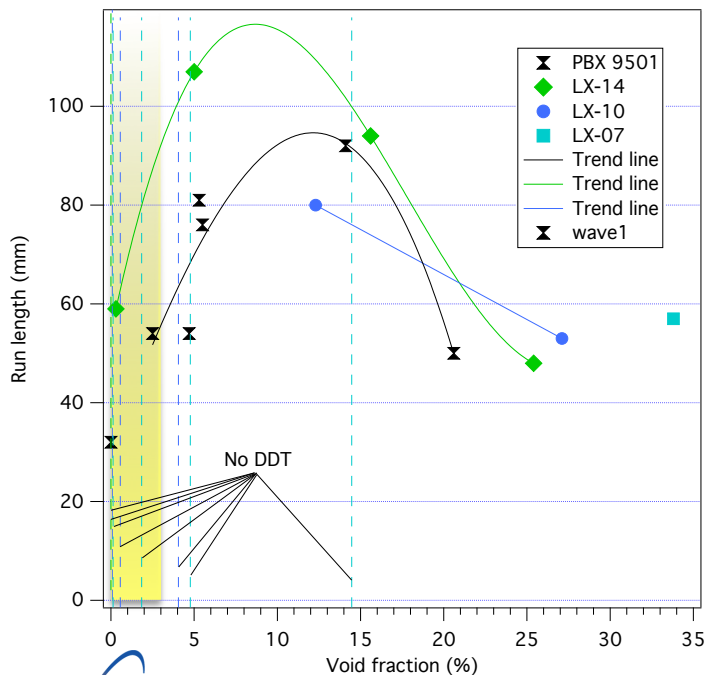
Results – How binder affects DDT run length

HE treatment:

Full ρ pressed cylinders, soaked for 3 hrs, end-ignited

Observations:

- PBX 9501 and LX-14 run lengths come back to being similar to highest void fraction tests
- LX-10 and LX-07 exhibit irregular burn progression (crack burning?)



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

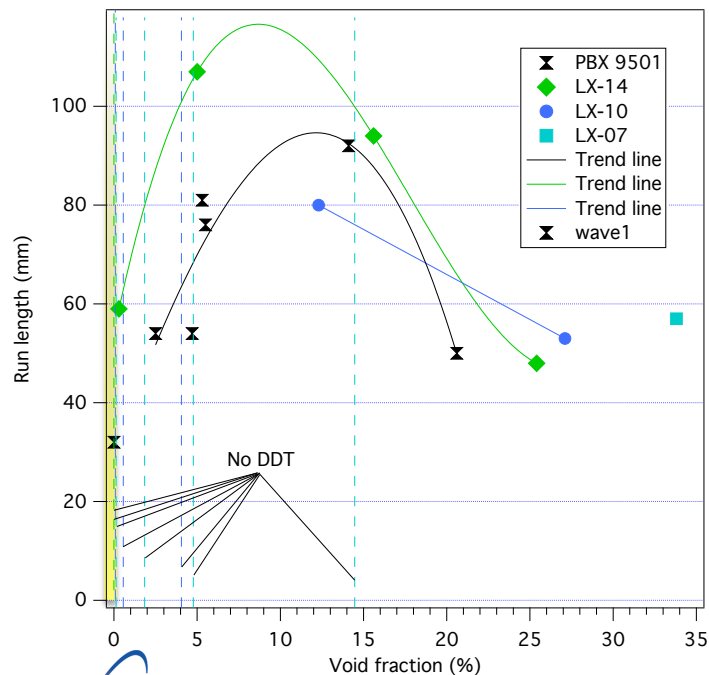
Results – How binder affects DDT run length

HE treatment:

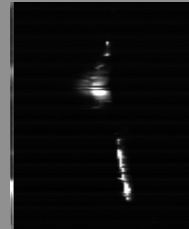
Full ρ pressed cylinders, ramped to cookoff as quickly as possible (rate $\sim 10^\circ\text{C min}^{-1}$)

Observations:

- PBX 9501 does not need much time at elevated temperature to become vulnerable to DDT



PBX 9501
~0% porosity
DDT



LX-10
~0% porosity
Violent burn



LX-14
~0% porosity
No streak, profile indicates no DDT
Violent burn

LX-07
~0% porosity
Violent burn



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

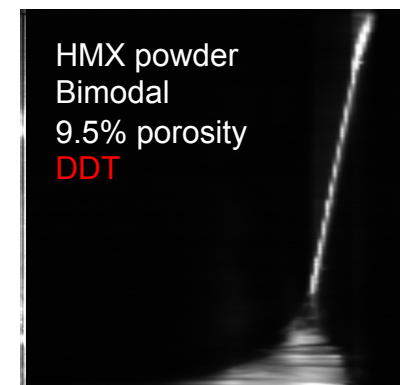
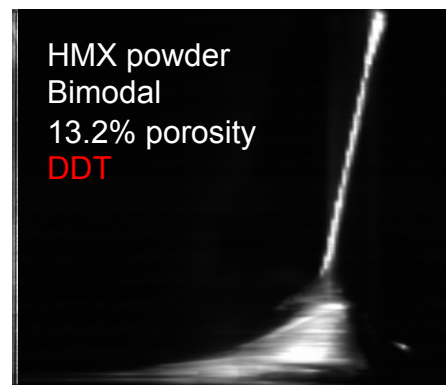
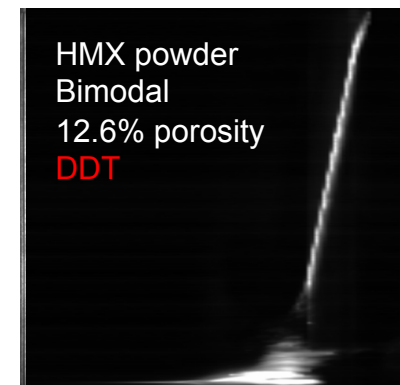
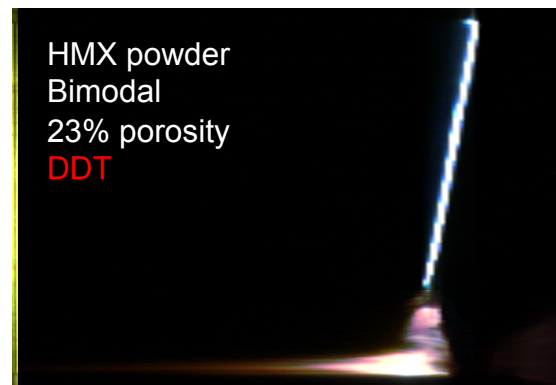
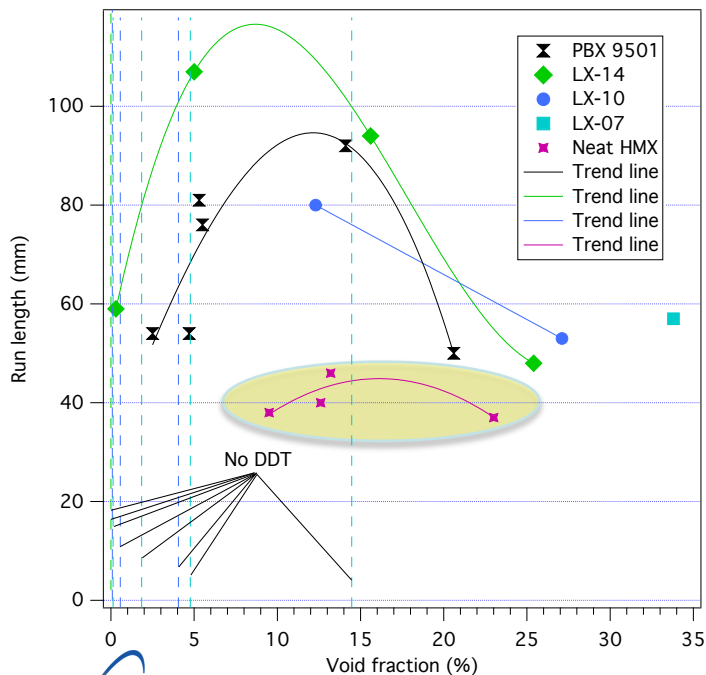
Results – How **lack of** binder affects DDT run length

HE treatment:

Hand tamped, neat HMX powder (bimodal particle size distribution), end-ignited at room temperature

Observations:

- Good repeatability
- Presence of binder increases DDT run length (*significantly at intermediate void fractions*)



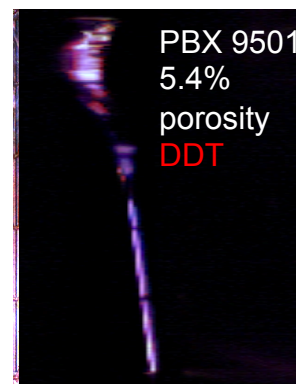
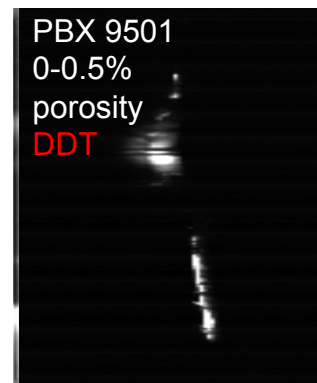
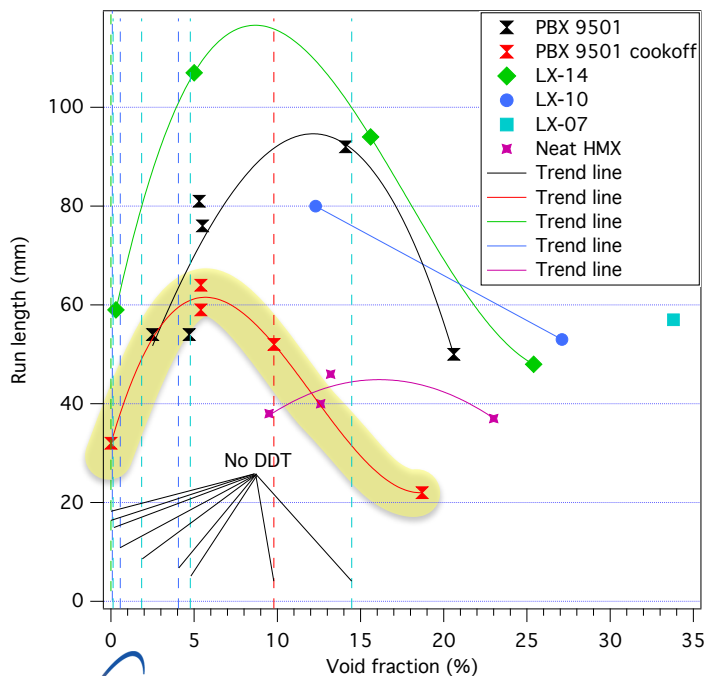
Results – PBX 9501 cookoff with post-ignition DDT

HE treatment:

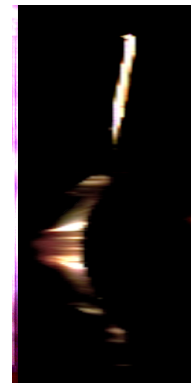
PBX 9501 with varied void fractions heated until self-ignition

Observations:

- DDT occurs in shorter distances following cookoff
- The trend line of run length vs. void fraction has similar concave-down curvature, with the longest run lengths occurring at low-to-intermediate void fractions



PBX 9501
9.8%
porosity
DDT



PBX 9501
18.7%
porosity
DDT



Conclusions

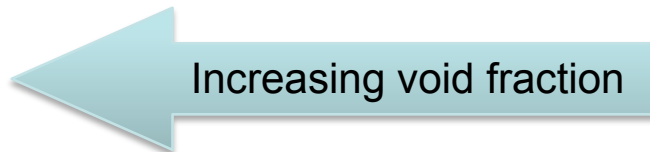
Hypothesis:

Void fraction effects:

- Increased void fraction → increased propensity for DDT & shorter run length

Conclusions

- All 4 formulations transitioned to detonation at the highest void fraction. However, these void fractions are beyond what one would expect from normal thermal damage.
- Only PBX 9501 and LX-14 detonated at low void fractions relevant to thermal safety issues.



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

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Conclusions

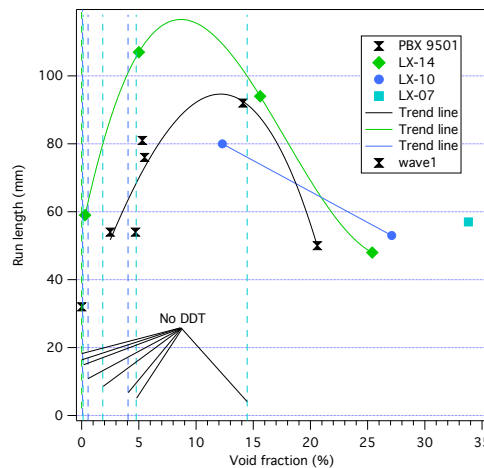
Hypothesis:

Void fraction effects:

- Increased void fraction → increased propensity for DDT & shorter run length

Conclusion

- The run length trend is not monotonic across the range of void fractions explored. At the highest and lowest void fraction tested, run length was similar, intermediate void fractions resulted in longer run lengths.
- This suggests competing processes may exist during the deflagration build-up.
 - At lower porosity, compressive burning dominates the build-up to thermal explosion
 - At higher porosity, convective burning dominates the build-up to thermal explosion



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The role of convective vs. compressive burning

Test:

PBX 9501, end-ignition at 185°C, HE impermeable Teflon barriers to block convective burn progression

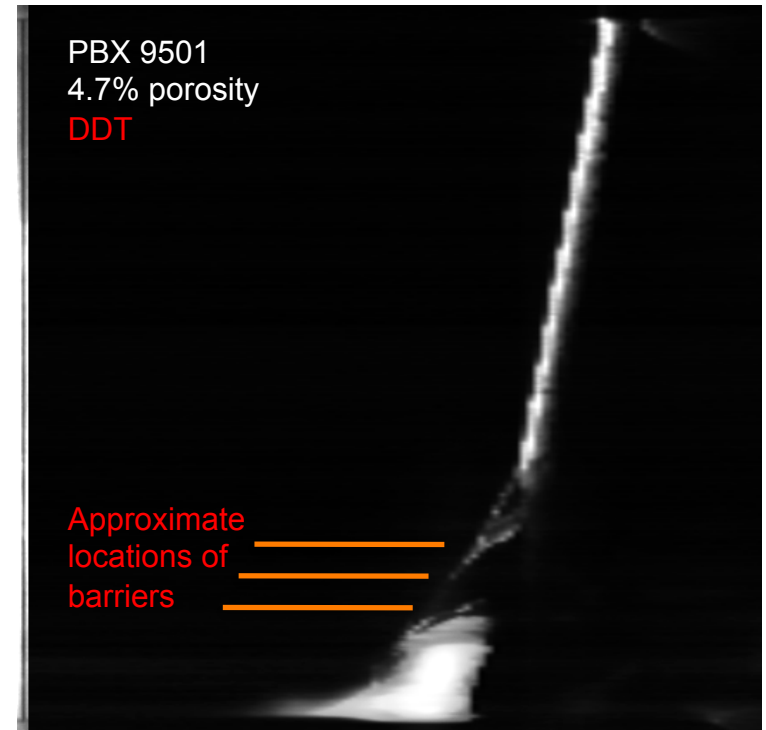
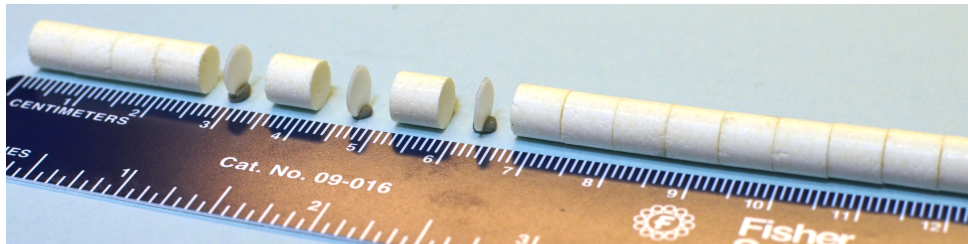
Result:

Barriers apparently stop convective burn. Compressive burn is evident, as is bed motion in the compaction region.

Conclusion:

Both convective and compressive burning occur... both may be necessary for DDT

With 3 Teflon barriers in HE column



Conclusions

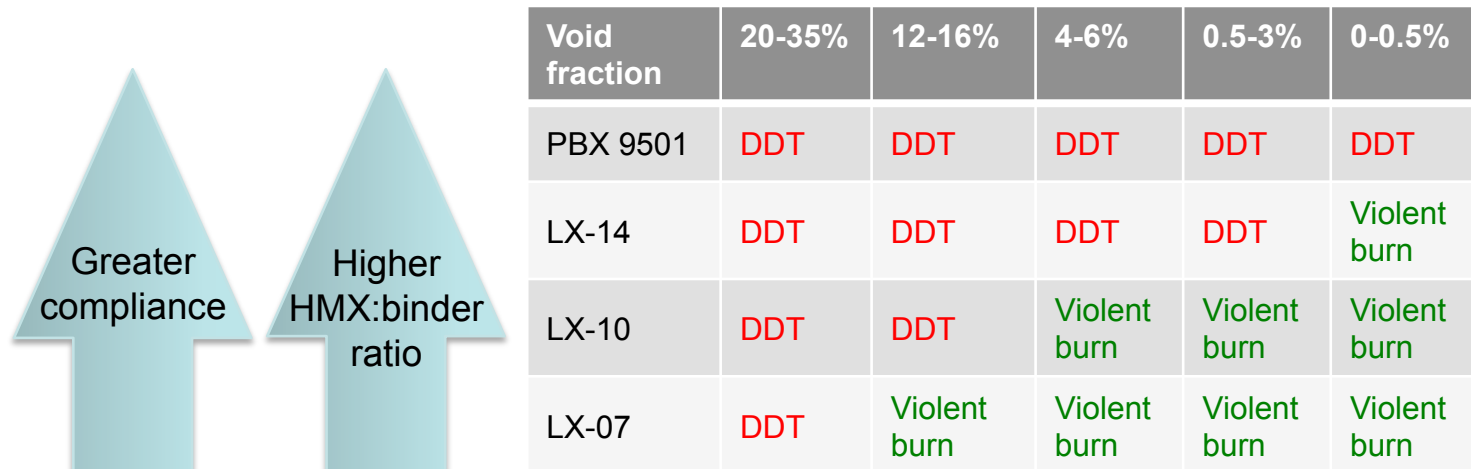
Hypotheses:

Binder system effects:

- Greater compliance of binder → increased propensity for DDT & shorter run length
- Higher HMX:binder fill fraction → increased propensity for DDT & shorter run length

Conclusion

- The HE with more compliant binder systems seem more likely to undergo DDT
- The ratio of HMX to binder also seems to affect DDT propensity in a direct relationship
- However, binder stiffness and HMX:binder ratio do not appear to correlate strongly with run length



Void fraction	20-35%	12-16%	4-6%	0.5-3%	0-0.5%
PBX 9501	DDT	DDT	DDT	DDT	DDT
LX-14	DDT	DDT	DDT	DDT	Violent burn
LX-10	DDT	DDT	Violent burn	Violent burn	Violent burn
LX-07	DDT	Violent burn	Violent burn	Violent burn	Violent burn

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Conclusions

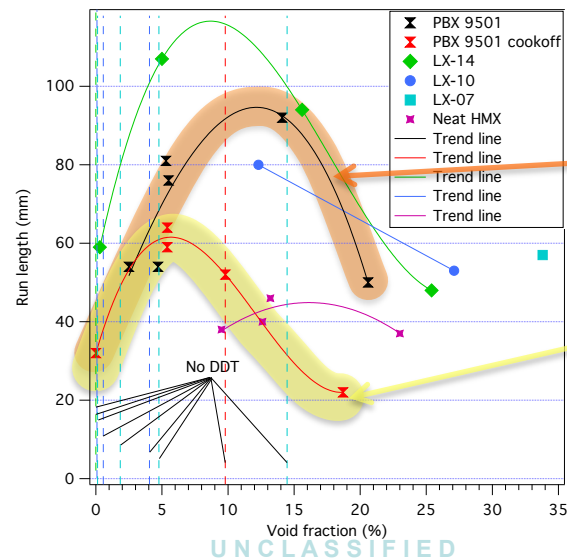
Hypothesis:

Cookoff effects:

- Thermal runaway to auto-ignition → increased propensity for DDT & shorter run length

Conclusion

- It is difficult to say if the propensity for DDT increases, because both the end-ignited and cooked off tests were done with PBX 9501 and it underwent DDT in all tests except one
- The run length in cookoff tests does significantly differ from end-ignited tests. Cookoff leads to shorter run lengths



End-ignited

Cookoff

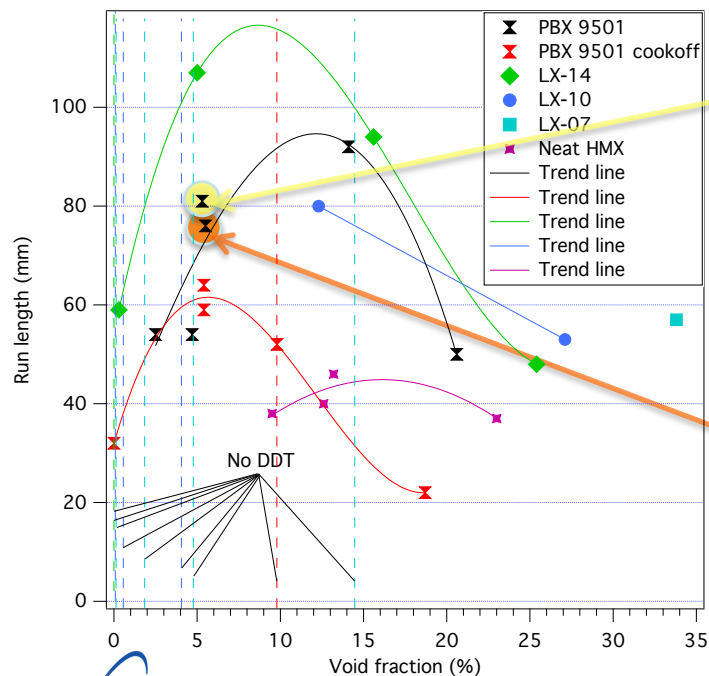
Why does cookoff produce shorter DDT run lengths?

Test:

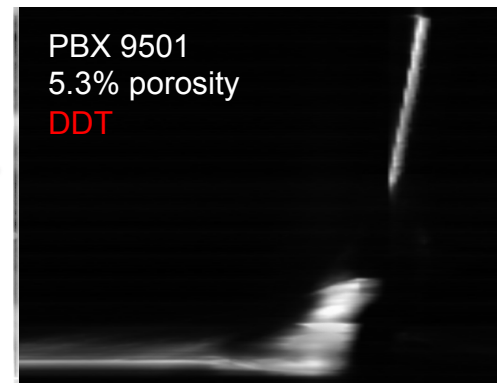
Compare two tests with similar void fractions and end-ignition, but different temperatures at ignition

Result:

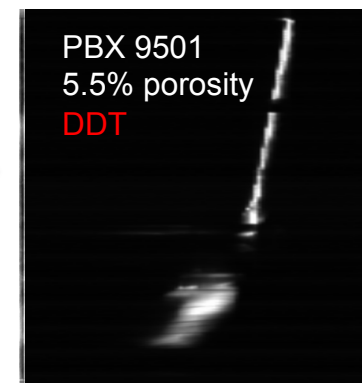
Similar run length → not simply a temperature effect



185°C



235°C



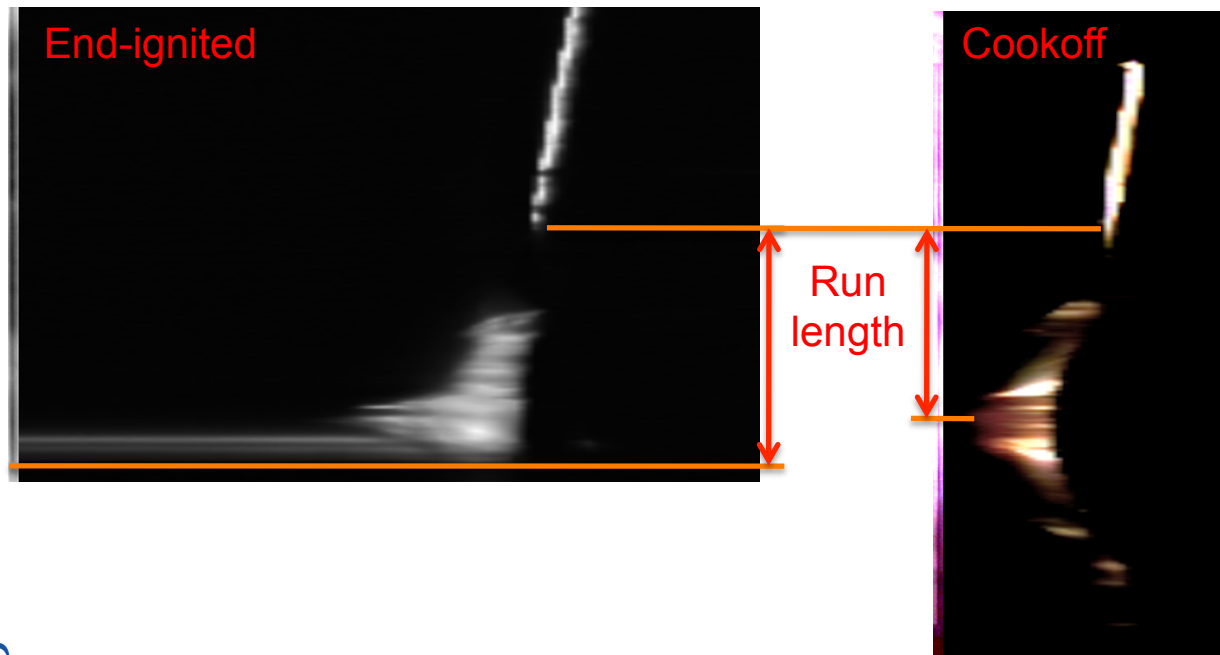
Why does cookoff produce shorter DDT run lengths?

Test:

Compare end-ignition to cookoff

Result:

Cooked off streak shows a shorter run length



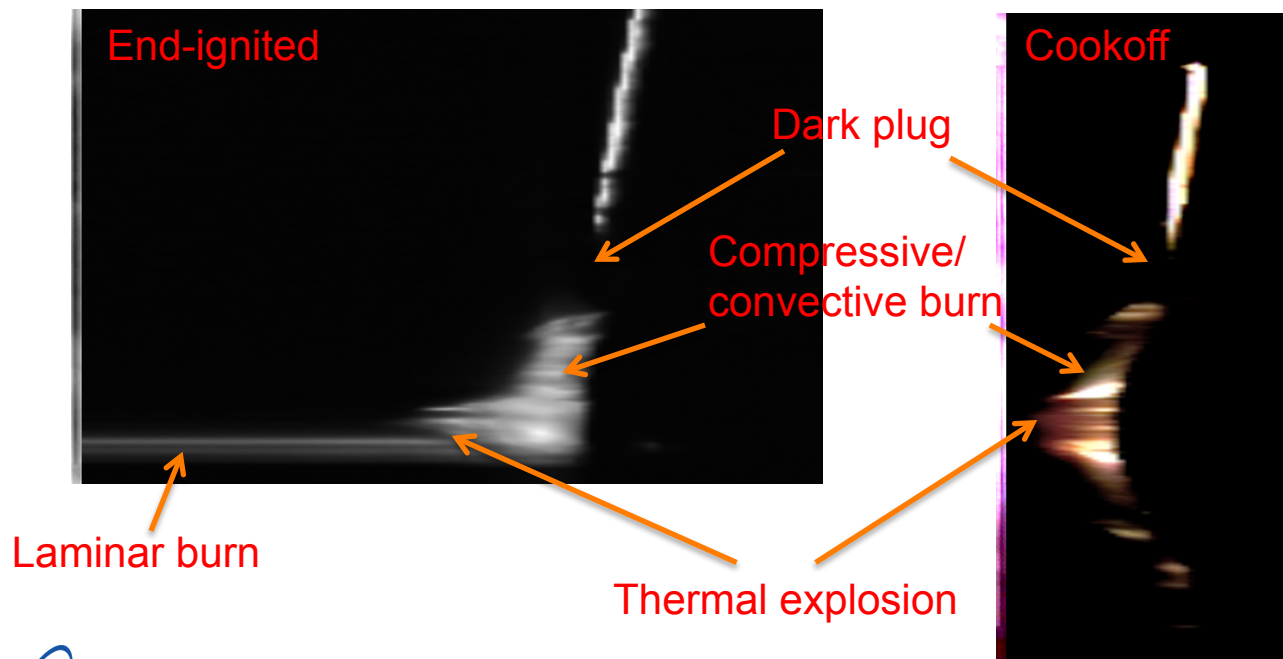
Why does cookoff produce shorter DDT run lengths?

Test:

Compare end-ignition to cookoff

Result:

Qualitatively similar, except there is no laminar burn mode in the cookoff test



Why does cookoff produce shorter DDT run lengths?

Test:

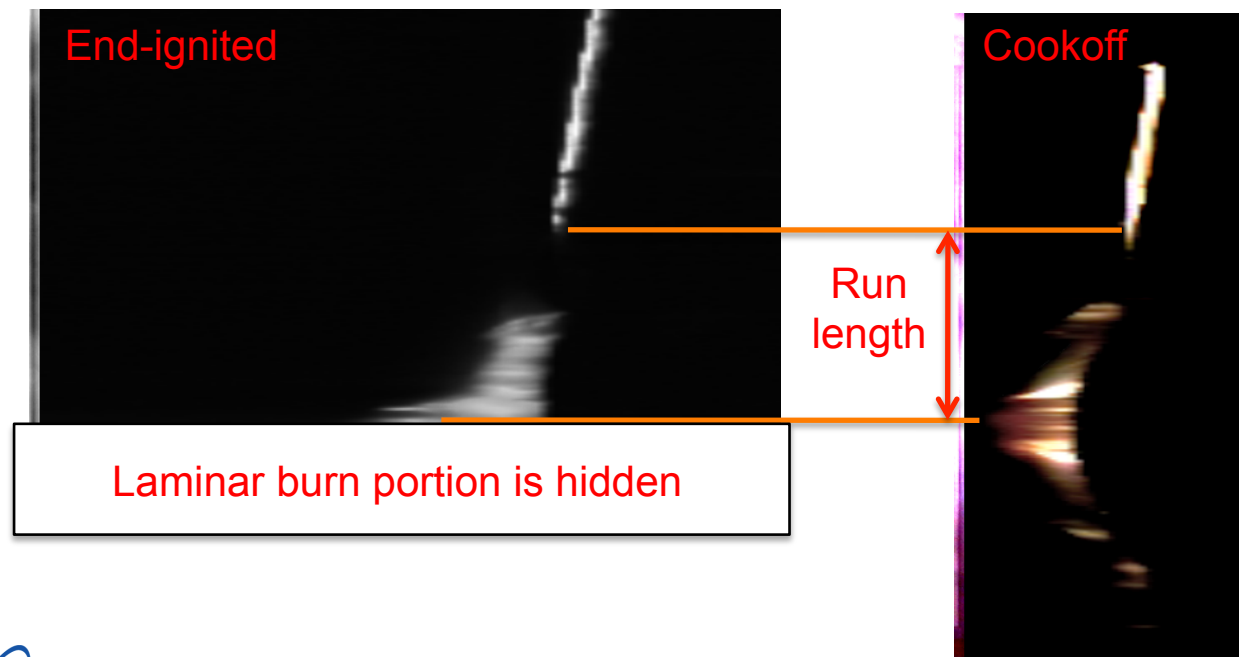
Compare end-ignition to cookoff, but disregard the laminar burn portion

Result:

Run lengths are similar without the laminar burn stage

Conclusion:

Cookoff initiates a thermal explosion and skips or abbreviates the early stages of burning that are part of the DDT build-up in end-ignited tests. From a safety perspective, where cookoff is relevant, this observation may simplify the problem somewhat.



Looking forward

We need to test more to understand the competition between compressive and convective burning in low porosity, thermally damaged PBXs.

- More barrier tests
- Radiography

If compressive burning is found to play the dominant role in DDT for thermally damaged PBXs, we may want to perform dynamic compaction tests on thermally damaged PBXs to develop crush-up models that accurately predict heating due to PV work.

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