# An Approach to Predict the Slow Cook-Off Response of Confined & Vented Munitions Based on Small Scale Tests

by

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# Approach for Scaling

1. Characterize the thermal degradation kinetics of PBXN-111 (before ignition)
   - Small scale tests to measure degradation rates of confined & vented material vs. $T(t)$
   - Develop degradation kinetics models from test data accounting for dependence on $T$ and venting
2. Examine the rate of combustion propagation in PBXN-111 (post-ignition)
   - Measure burn rates of pristine, heated and thermally degraded PBXN-111 in a strand burner vs. $P$
   - Develop models for burn rate vs. extent of thermal degradation ($\phi$), $P$, and $T$
3. Develop fast running engineering models for
   - Ignition: predict $T(x,t)$ & $\phi(x,t)$ until ignition, and $T_{wall}$ & $P$ at ignition accounting for venting
   - Combustion: predict $P(t)$, $dP/dt(t)$ and dimensions of burned region accounting for the effects of $T$, $P$, $\phi$ & venting on burn rate
4. Model validation: compare $T_{wall}$ at ignition predicted by the model with
   - Small scale cook-off tests by BlazeTech/Sandia
   - Larger scale tests by the Navy

*The BlazeTech model can be used to predict the cook-off response of full-scale munitions loaded with PBXN-111 to heat accounting for venting*



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# Step 1. Thermal Degradation of PBXN-111

- PBXN-111: 43% AP, 25% Al, 20% RDX, and 12% HTPB/IDP binder system
- Measure thermal degradation rates vs. *T(t)* to generate easy-to-use kinetics data
- Test setup
  - Small scale, 1/4”×1/4” pellets (~2 g/test) & slow heating → uniform temperature throughout
  - Two configurations: confined (8 tests) and vented (8 tests)
- Test procedure
  - Heat to 150 – 175°C and hold for 4 – 32 hours (conditions designed to preclude ignition)
  - Measure five $T(t)$ (3 on casing), explosive, oven, and when confined $P(t)$
  - Turn heater off. Monitor $T(t)$ (and $P(t)$) during cool down
  - Measure mass loss due to thermal degradation by comparing pre- and post-test masses
- Data analysis: For each test,
  - Determine the time for which the explosive is hotter than 130 C
  - Determine the time-averaged temperature for that duration
  - Calculate the % mass loss from pre-test and post-test mass measurements
  - Develop kinetic model to calculate $m(t)$ from measured $P(t)$ and $T(t)$


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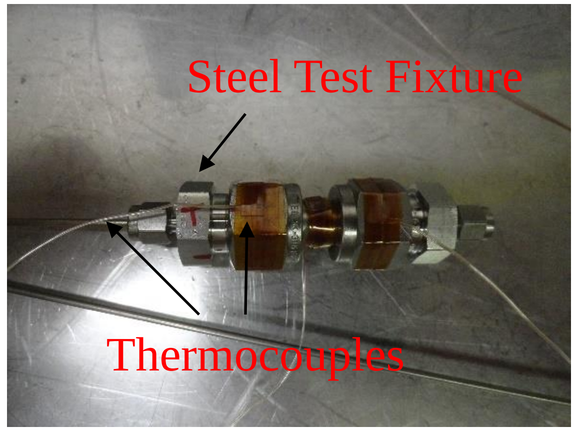
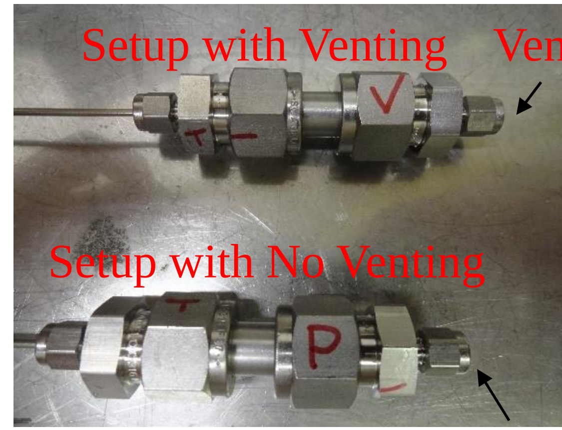
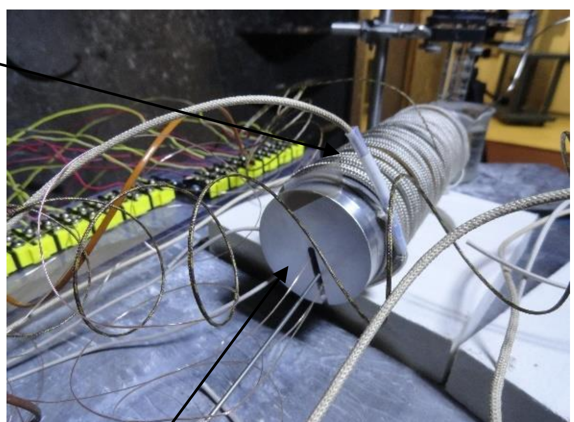
# Assembly Procedure

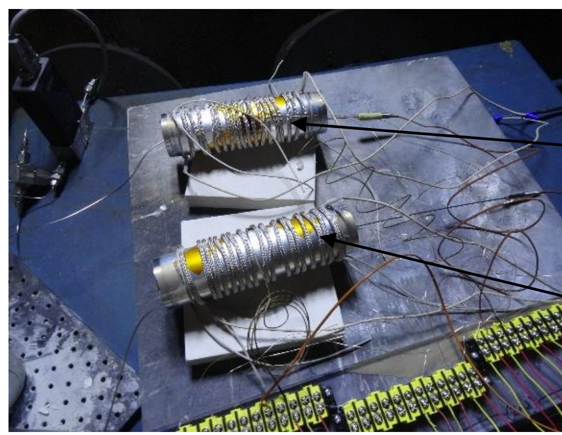




To Pressure Transducer

Heater



Al Oven



Setup with No Venting (confined)

Setup with Venting (partially confined)



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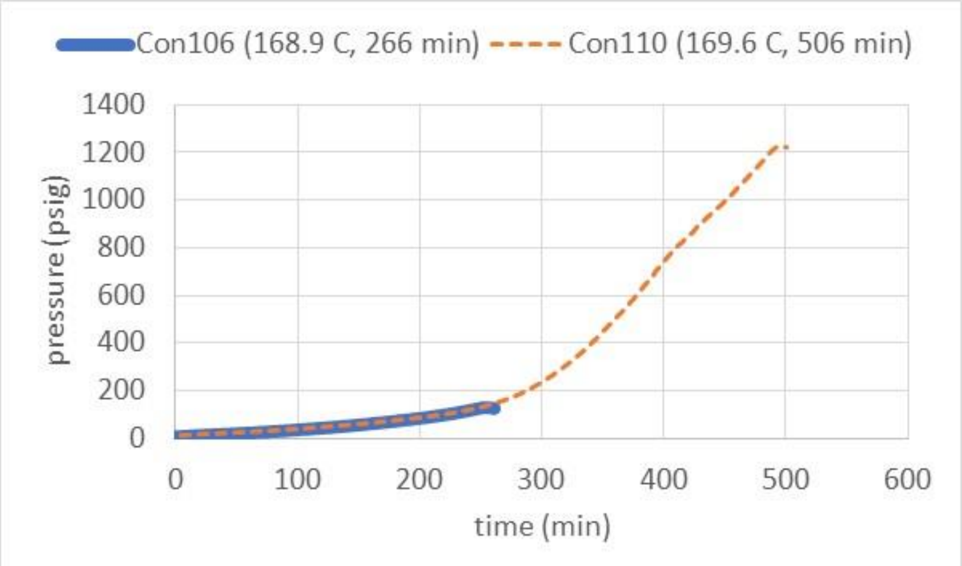
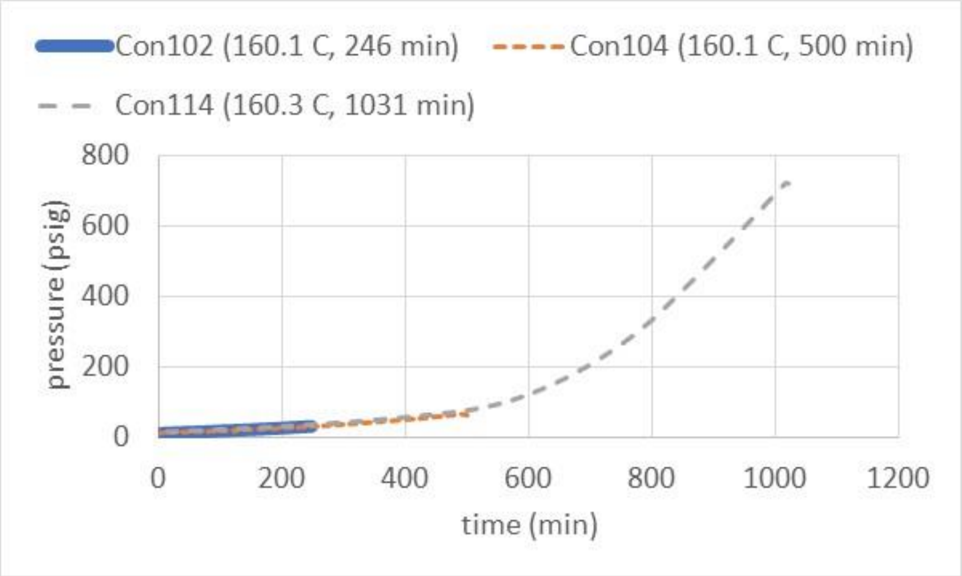
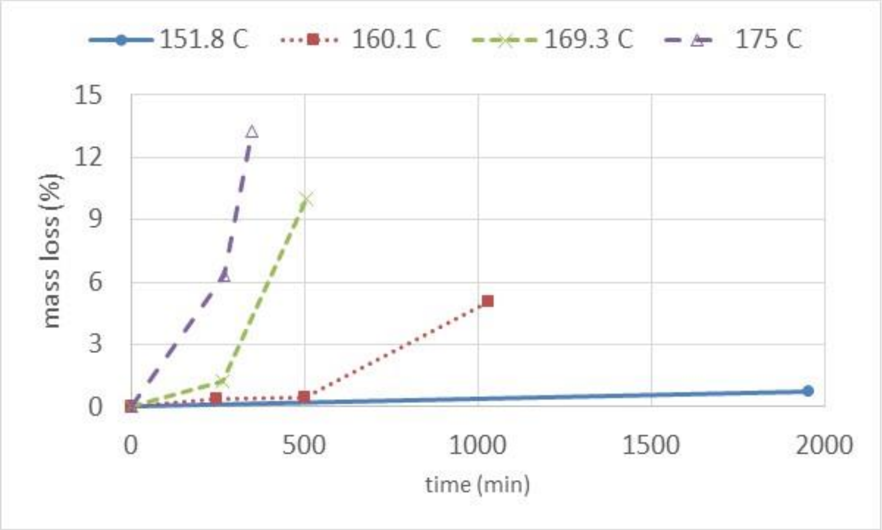
# Confined Tests: Effects of T(t) on *P*(*t*) and m(t)

**Pressure Rise, P(t)**




**Mass Loss, m(t)**



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# Thermal Degradation Kinetics of PBXN-111

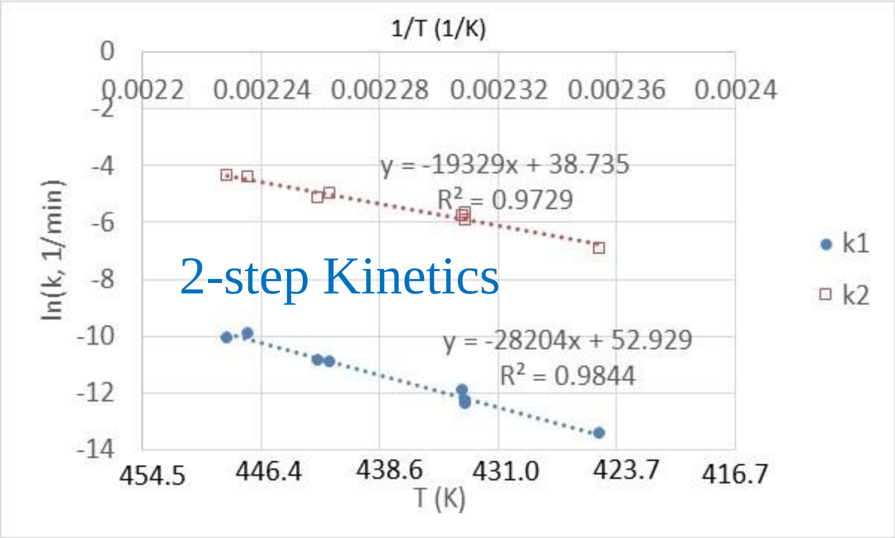
**Post-Test Photographs After Exposure to ~160 C for 1030 minutes**

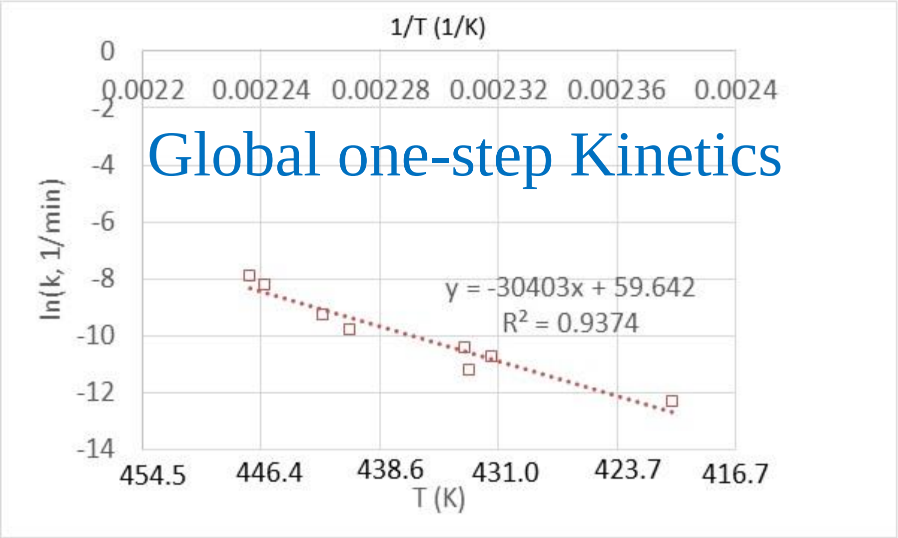
Confined Test Con114: 5.05% mass loss

Vented Test Con115: 2.93% mass loss

**Confined**

**Vented**




Thermal degradation rate increases with confinement



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# Step 2. Burn Rate of PBXN-111

- Measure burn rates vs. *T*, *P* and extent of thermal degradation ($\phi$) in a strand burner
- 3 types of PBXN-111: pristine (2 tests), heated (4 tests) and thermally degraded (4 tests)
- Test procedure
  - Install ignitor, 2 thermocouples and 6 break wires in a PBXN-111 strand made from 8 cylindrical (1/4”×1/4”) pellets
  - Fill strand burner with an inert gas to target initial pressure
  - Heat the entire strand burner to a desired temperature and hold to induce thermal degradation
  - Ignite the vertically oriented explosive strand at the top
  - Detect burn front arrival at various locations, $x(t)$, using the thermocouples and break wires
  - Record $P(t)$, $T(t)$ and $x(t)$
- Data analysis: In each test,
  - For various $T(t)$, calculate $\phi$ at end of heating period using the kinetic rates model
  - Generate *x*-*t* plots for the combustion front for various *P* and for $\phi$ at end of heating period
  - Fit appropriate curves through the *x*-*t* plots. Determine the burn rates and accelerations


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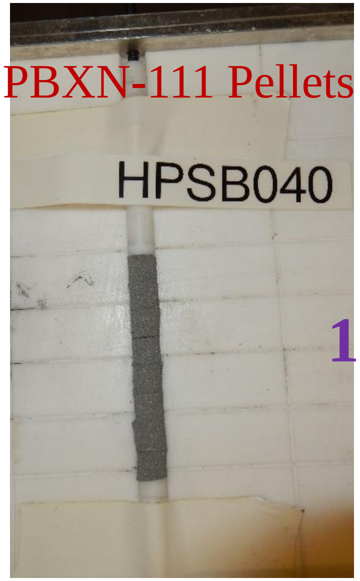
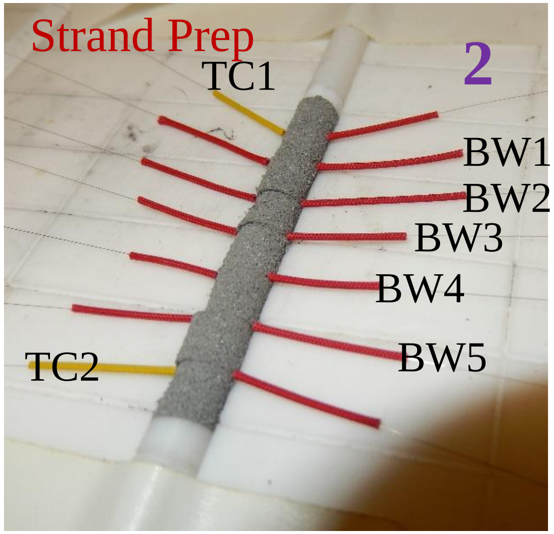
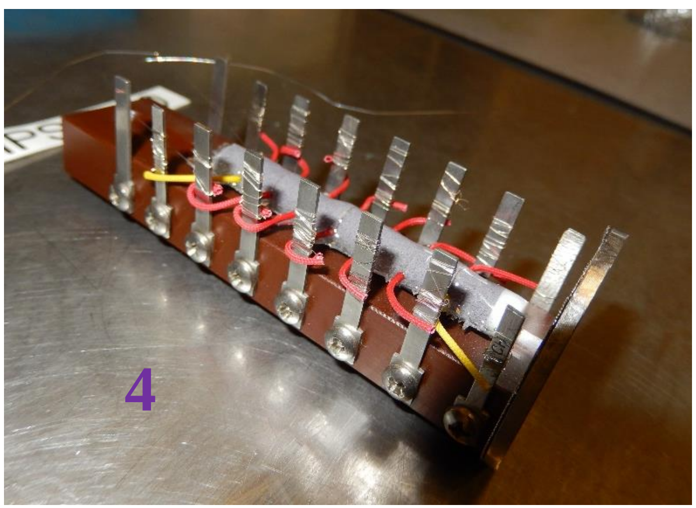
# Assembly Sequence

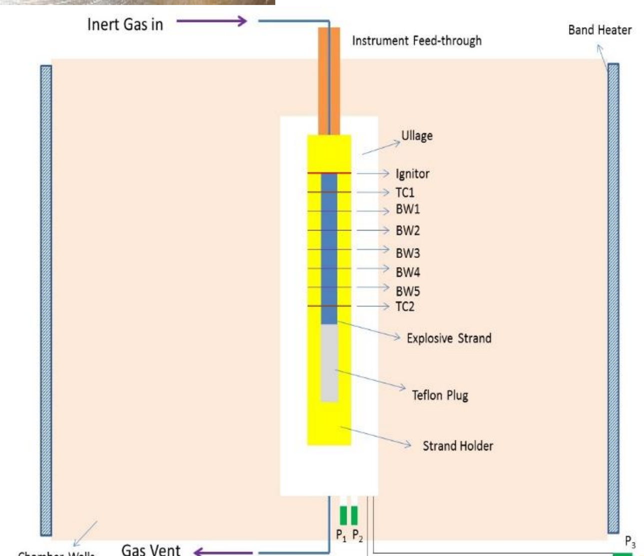










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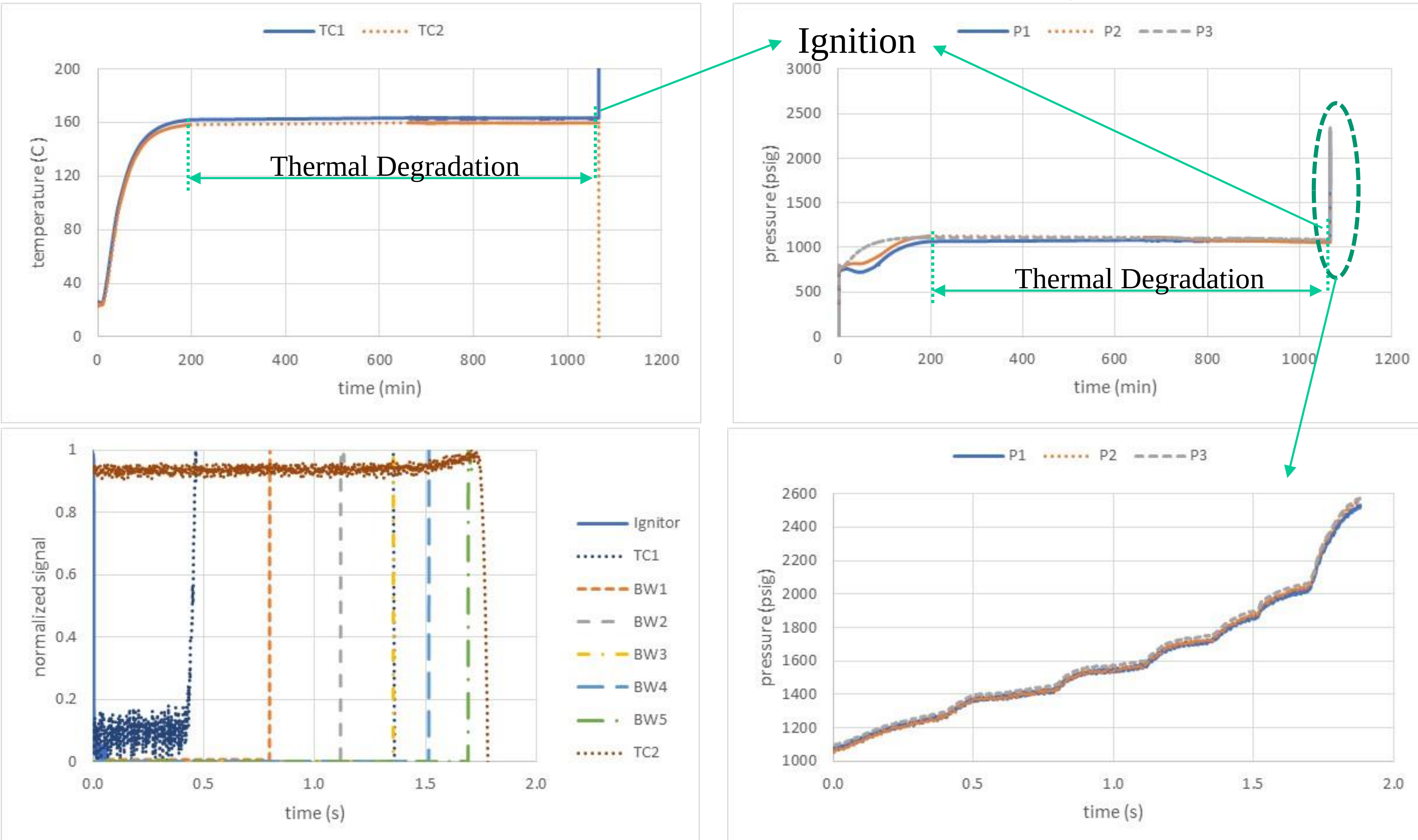
# Sample Data from PBXN-111 Burn Test

## Strand Exposed to 160°C for 16 hours before ignition




Rates of burn propagation & pressure rise increase with time



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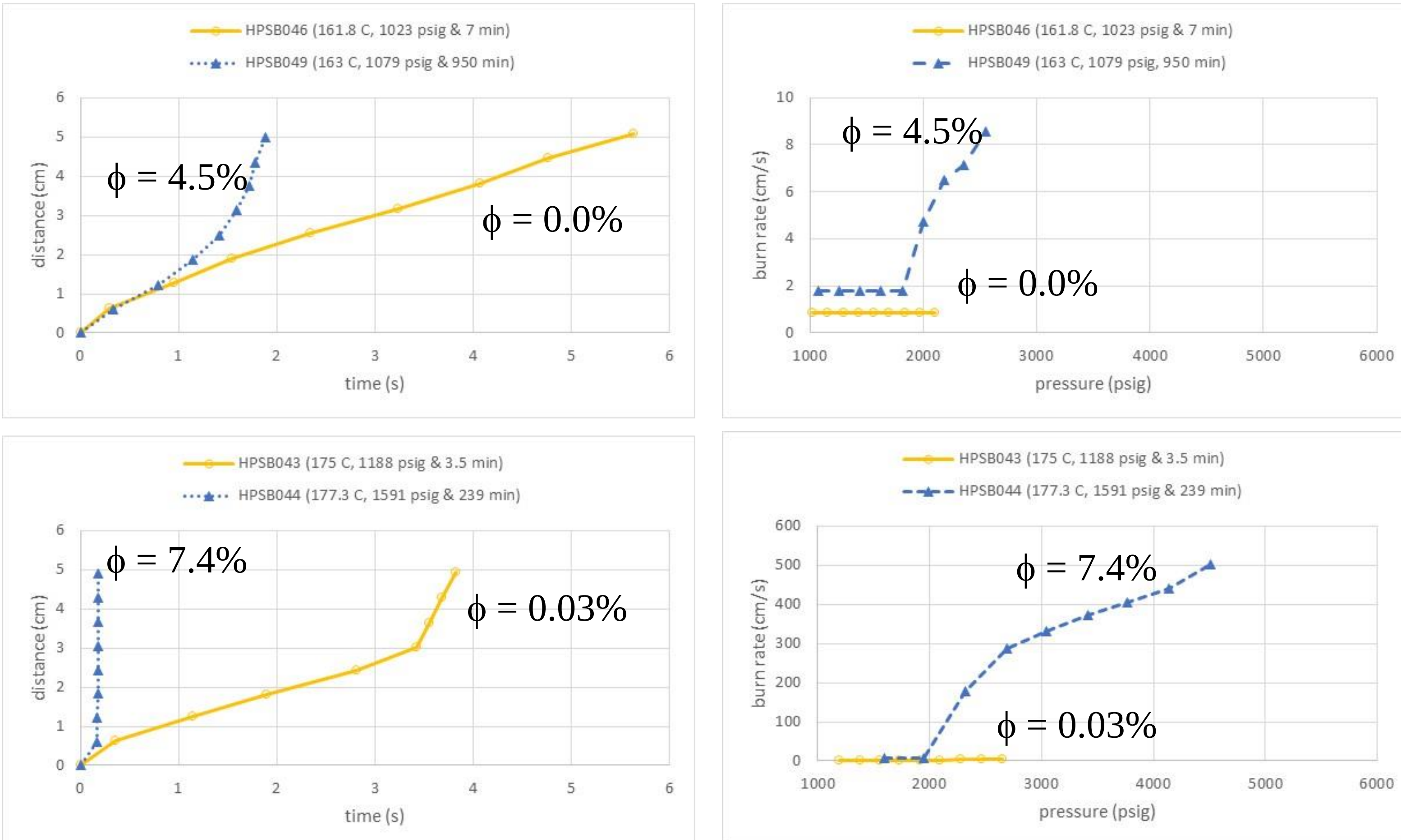
# Effect of Thermal Degradation on Burn Rate




- Extent of thermal degradation ($\phi$) estimated for each test using our kinetics model
- Undegraded PBXN-111: burn rate constant, but increases at 2000 psig
- Degraded PBXN-111: (i) $P < 2000$ psig: constant burn rate; (ii) $P > 2000$ psig: burn front accelerates with increasing $\phi$ and $P$



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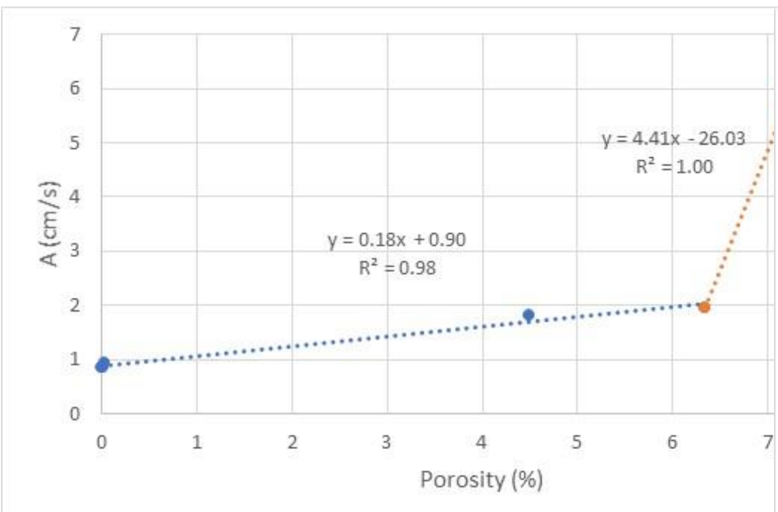
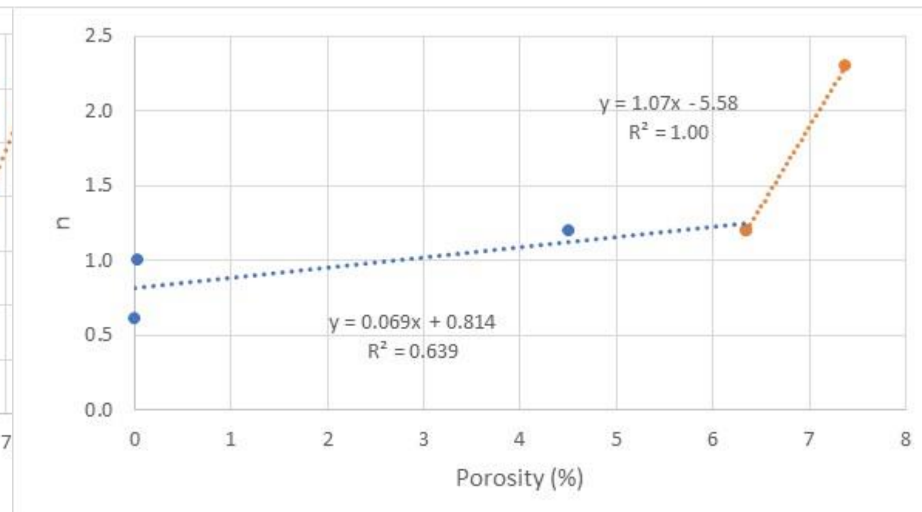
# Burn Rate Model

$$u = A(\phi) \times P^{n(\phi)}$$

P<2000 psig $\begin{cases} A = f(\phi) \\ n = 0 \end{cases}$ P>2000 psig $\begin{cases} \text{A=0.22 cm/s/MPa}^n \\ n = \text{f}(\phi) \end{cases}$




- $\phi$ = extent of thermal degradation related to porosity (%) assuming uniform mass loss
- Slopes of burn rate parameters vs. *P* curves increase significantly at $\phi > 6.35\%$
- *u:* cm/s, *P*: MPa



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# Step 3. Model Development

## A. Ignition Sub-Model

**- Fast running 1-d model**

**- Inputs**

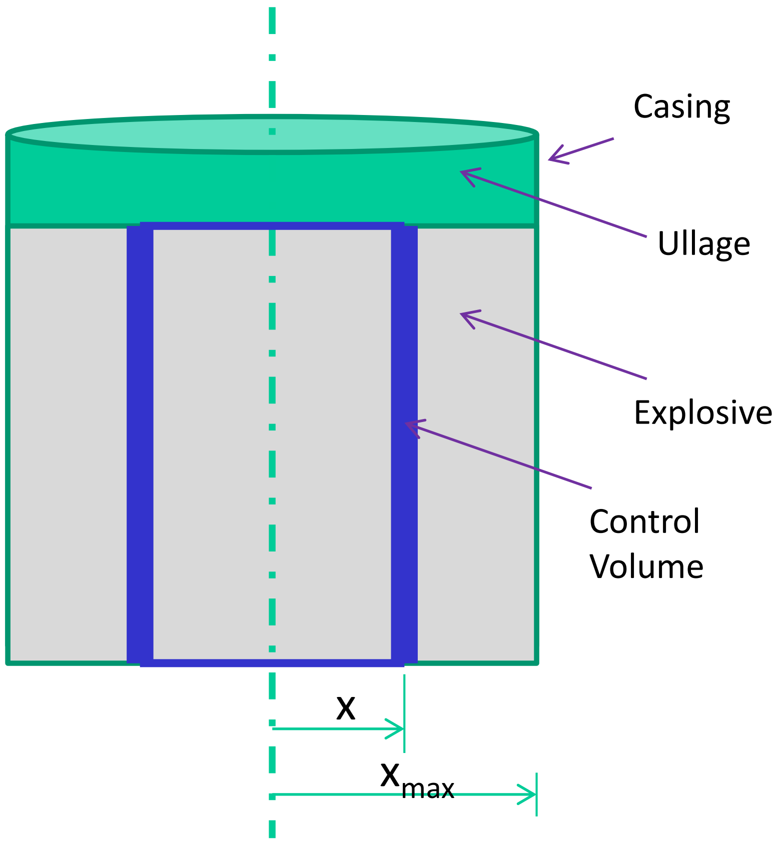
- Geometry: explosive & casing
- Heating: $T_{initial} \rightarrow T_{soak} \rightarrow T_{final}$ and durations
- Venting: onset *P* for venting and vent diameter

**- Model tracks**

- Heat conduction, thermal expansion
- Thermal degradation and morphology changes
- Venting: shift in reaction kinetics
- Changes in *P*: (i) heat & gas generation from degradation reactions, and (ii) venting losses
- Ignition when *T* inside explosive >> $T_{wall}$

**- Outputs**

- $T(x,t)$, $\phi(x,t)$ and $P(t)$
- Occurrence of ignition: its time and location



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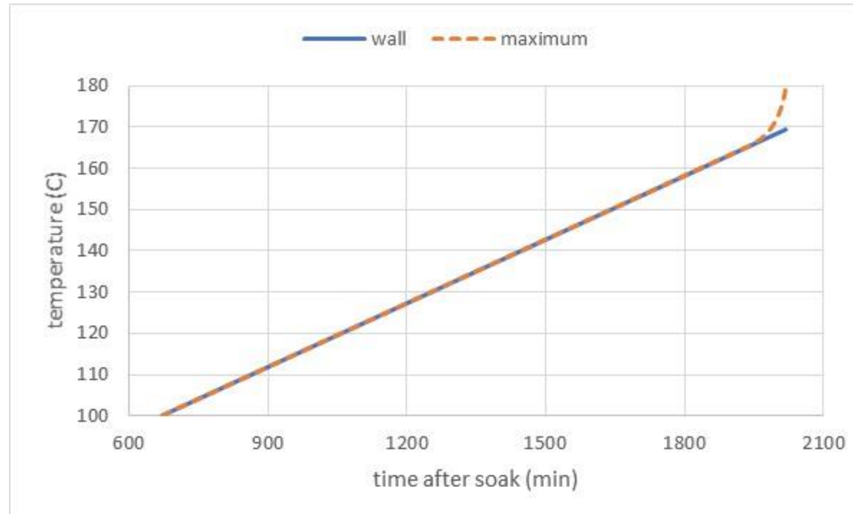
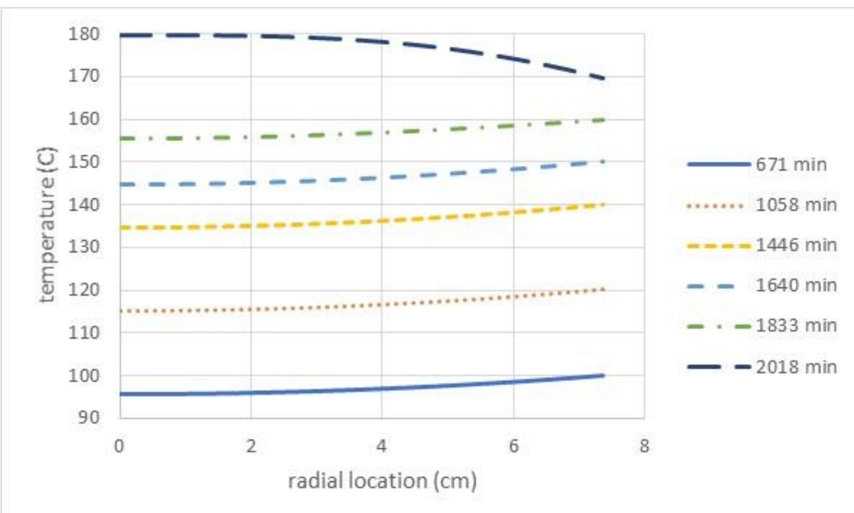
# Sample Calculation: Navy Sub-Scale Test 1

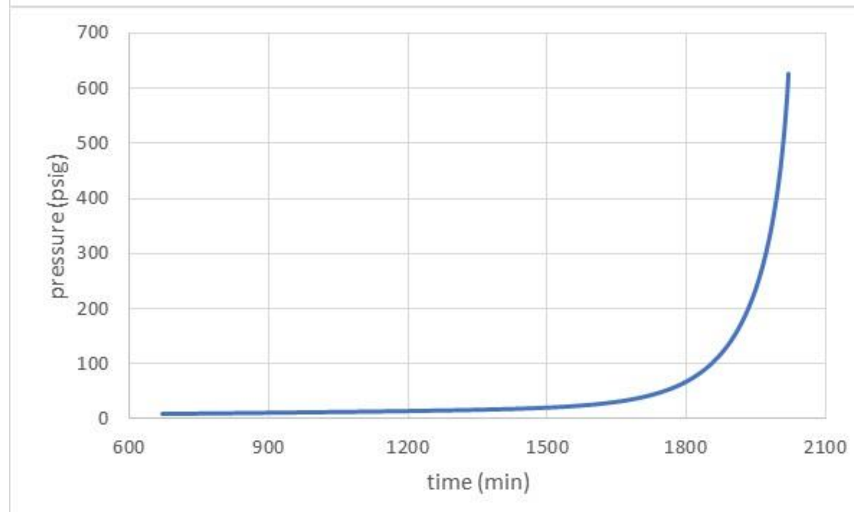
- 6690 g (D ~ 14.74 cm, L ~ 21.9 cm) [1,2]
- Heating Profile: 8 hour soak at 65.6°C, then 0.052°C/min until ignition

| | Test | Model |
|---|---|---|
| Ignition Time, min | 1960 | 2018 |
| $T_{wall}$ @ ignition, °C | 166.5 | 169.6 |

- Model predicts $T(x,t)$, $P$ and $\phi$ that are difficult to measure accurately




[1, 2] Beckett, et al, 39th PEDCS, JANNAF Meeting, Salt Lake City, Utah, 12/7-10/2015.

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# B. Combustion Sub-Model

**- Fast running engineering model**

**- Inputs**

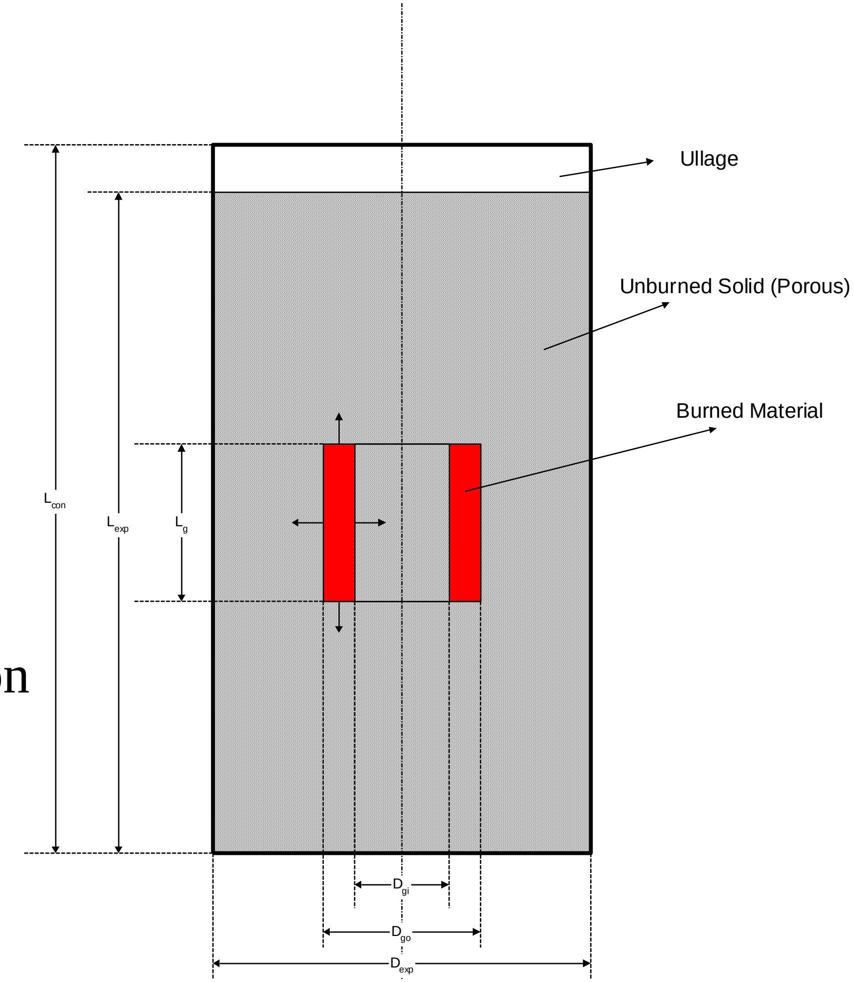
- Geometry: explosive & casing
- Ignition location
- Conditions at ignition: $T$, $P$, $\phi$
- Vent onset pressure and diameter

**- Model tracks**

- Burn front propagation
- Heat/gas generation by combustion
- Energy losses from burned region

**- Model outputs**

- $P(t)$, $T_{burned}(t)$, $m_{exp}(t)$, dimensions of burned region vs. $t$



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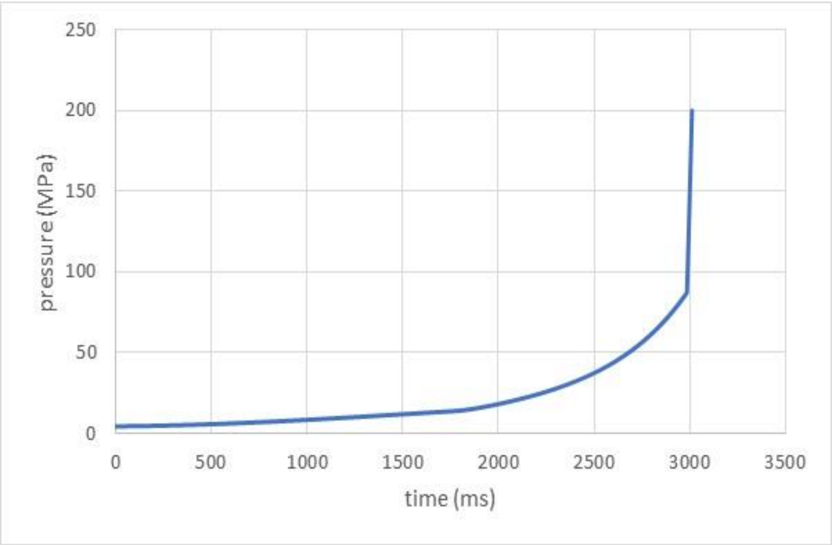
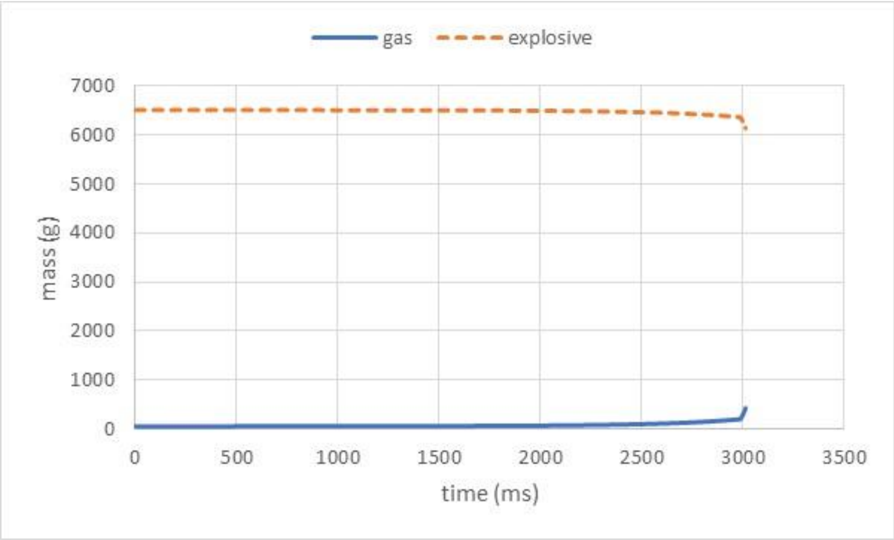
# Sample Calculation: Navy Sub-Scale Test 1

- 6690 g of PBXN-111 (D ~ 14.74 cm, L~ 21.9 cm) [1,2]
- Ignition location: explosive center
- Conditions at ignition:
  - Pressure = 626 psig (4.3 MPa)
  - Mean porosity ~ 0.4%
- Container assumed to fail at 200 MPa→ we stopped the combustion calculation




[1, 2] Beckett, et al, 39th PEDCS, JANNAF Meeting, Salt Lake City, Utah, 12/7-10/2015.



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# Step 4. Model Validation

- **Limited literature data to validate ignition model and none for combustion model**
- **BlazeTech/SNL performed 8 small-scale cook-off tests to generate additional data:**
  - 2 confined, 2 vented, 4 small leaks. Violent cookoff did not occur in tests with venting: we used the occurrence of significant self-heating as indicative of ignition

| | BlazeTech/SNL | VCCT [3] | Sub-scale [1, 2] | Max/Min of Range |
|---|---|---|---|---|
| Explosive Mass (g) | 2.09 | 57.6 | 6690 | 3200 |
| Explosive Radius (cm) | 0.309 | 1.27 | 7.37 | 24 |
| Explosive Length (cm) | 3.8 | 6.35 | 21.9 | 5.8 |
| Ullage Volume (%) | 45 | ~10 | ~10 | 4.5 |
| Final Heating Rate (°C/min) | 0.05 to 0.406 | 0.055 | 0.0515 to 0.479 | 9.6 |



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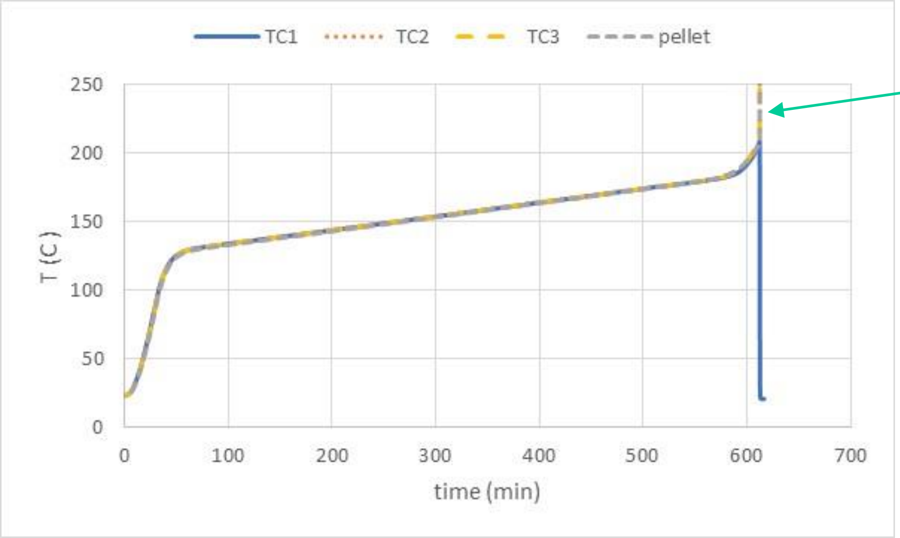
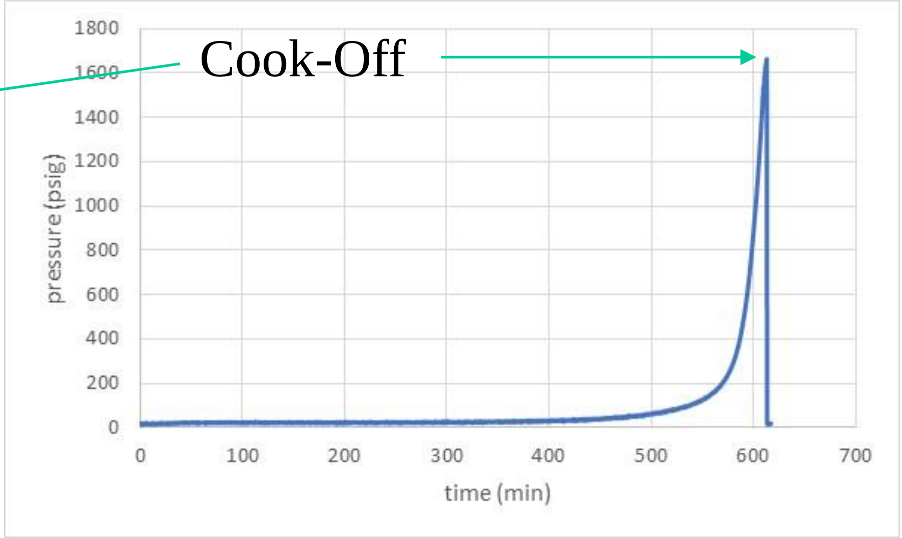
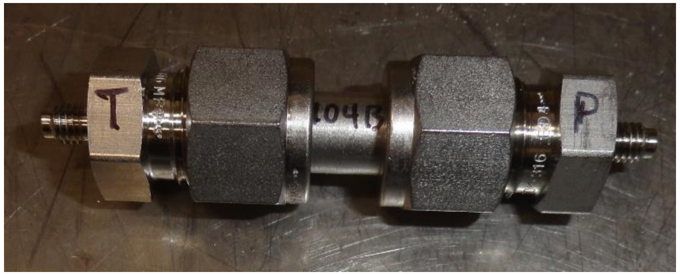
# Data from Cook-Off Test at 0.1°C/min

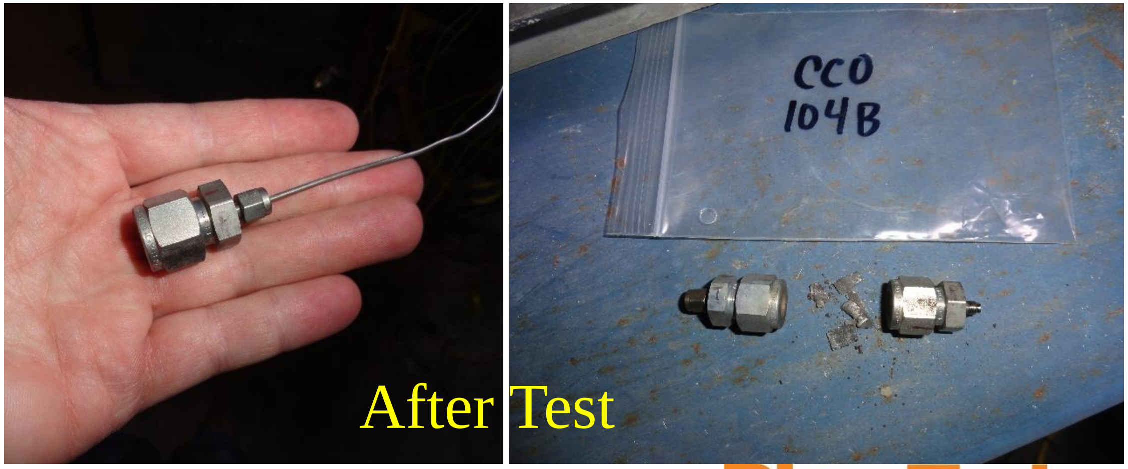



Cook-Off




Before Test




After Test



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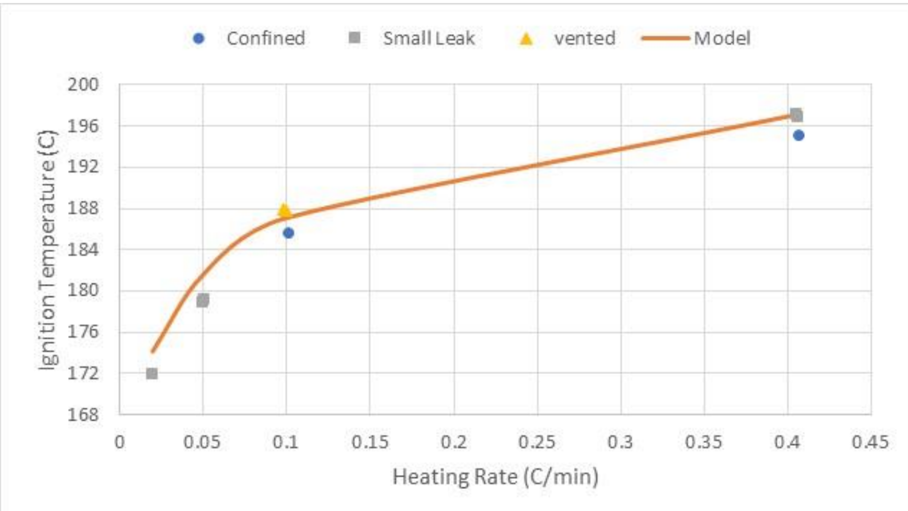
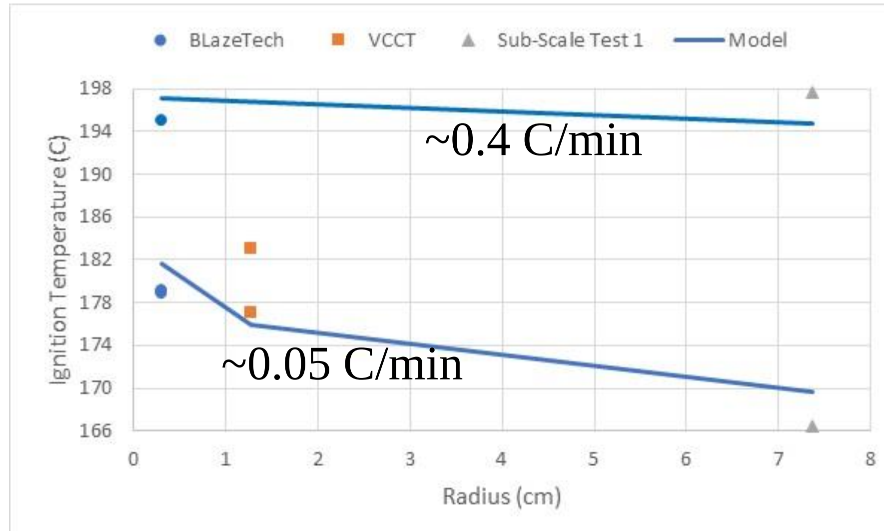
# $T_{ignition}$ for Various Sub-Scale Cook-Off Tests: Model Predictions vs. Measurements

**Effect of Heating Rate on $T_{ignition}$**
BlazeTech/SNL Tests, R = 0.309 cm




**Effect of Scale on $T_{ignition}$**
Three Separate Studies




- Ignition temperature (i) is almost independent of venting, (ii) increases with heating rate, and (iii) decreases with increasing size
- Model predictions agree well with a range of test data



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# Effect of Venting on Slow Cook-Off

- Venting affects thermal degradation reactions and combustion of PBXN-111
- Effects on thermal degradation (before ignition)
  - Gaseous reaction intermediates/products are released from the munition
  - Thermal degradation at a given $T$ is slower for vented than confined material
  - A small vent at a low $P$ could prevent pressure buildup
- Effects of venting on burn rate, $u$ (after ignition)
  - $u$ depends on extent of thermal degradation and $P$ which is lowered by venting
  - $P < 2000$ psig, $u$ remains constant
  - $P > 2000$ psig, $u$ increases and may accelerate (depends on degradation)
  - Early and adequate venting to ensure that $P<2000$ psig will reduce SCO violence
- Our small-scale cook-off tests on PBXN-111 have shown that
  - Completely confined material underwent violent cook-off (case fragmentation)
  - Vented material (leak in casing) underwent self-heating but not violent cook-off



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# Conclusions

**- From testing and analysis, we have quantified:**

- The pre-ignition thermal degradation rates = f($T$, $t$ and confinement)
- The post-ignition burn rate, $u$= f($P$ & $\phi$ at ignition), $u$ can vary by orders of magnitude with a threshold in sensitivity ~ 2000 psig

**- We developed an engineering model of cook-off using these rates. It predicts:**

- The time and spatial evolution of $T$, thermal degradation, burn front, unburnt and burn mass as well as $P(t)$, the latter is indicative of severity
- The ignition temp. increases with heating rate (for a given size) and decreases with size (for a given heating rate), which is validated by the available data
- We seek additional data for model validation

**- The model outputs can be coupled to a structural code to predict case fragmentation and collateral damage**

**- Our work can be extended to other munitions and used in the design of future tests and of vents**



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