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Integrated Violence Model (IVM) of 1.3 Events

by

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Introduction

- **Ignition** of 1.3 energetic substances (pyrotechnics, propellants, and explosives) **can lead to** the **production of significant amounts of hot gases**
- If those gases are confined within a structure, equipment, or device the pressure can rapidly increase and result in an explosive event (fragmentation, overpressure, heat flux)
- Sufficient venting can prevent an explosive event
- The Integrated Violence Model (IVM) has been used successfully to determine necessary vent areas and estimate the associated reaction violence

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Integrated Violence Model (IVM)

- Initially developed in 2011 to estimate the violence (overpressure, pressure rate-or-rise, and fragment velocity) of a **deflagrating** rocket motor
- It is not a molecular dynamics code (molecules are tracked through time and space) or a computational fluid dynamics code (properties of thousands of collections of control volumes are tracked through time).
- IVM determines the pressure and temperature of up to a dozen control volumes with gaseous inputs and outputs.
- It is not a one size fits all and in some cases the lack of spatial resolution is insufficient to accurately evaluate complex spatially depended phenomena such as interacting blast waves

Integrated Violence Model (IVM) cont.

- IVM is **based on thermodynamics principles** including conservation of energy and mass. IVM requires **small-scale testing** to determine critical parameter values.
- It has been used successfully to determine necessary venting areas and reaction violence for more than a dozen 1.3 events
- Highlighted here is its application to the NAWCWD TM 8742 testing of M1 propellant within a concrete structure
- IVM accurately predicts the test outcomes

Presentation Outline

- IVM Model Structure Highlighted
- Example determination of critical parameters and evaluation of the model's infrastructure
- Summary of scenarios where the Integrated Violence Model has been applied
- Application of IVM to TM 8742 testing
- Summary

IVM Model Structure

Model Input

Critical parameters

- Burn rate
- Burn rate pressure exponent
- Moles of gas/kg
- Heat capacity of combustion gases
- Confining medium geometry and characteristics
- Vent area characteristics
- Substance mass

→

Model Infrastructure

Integrated modules

- Pressurization
- Venting
- Kinetics (zero, 1st, 2nd order, etc.)
- Heat transfer
- Scaling effects
- Fire-ball size
- Heat flux
- Overpressure
- Afterburning
- Etc.

→

Model Output

- Internal pressure
- Internal pressure rate-of-rise
- Overpressure
- Fragment velocities

IVM Utilization Steps

1. **Determine model inputs** from small-scale testing and/ or literature values
2. **Complete Infrastructure Check** to determine if the model is properly configured
3. **Complete model prediction** of the system of interest
4. **Compare** model prediction to experimental results when available for **model validation**

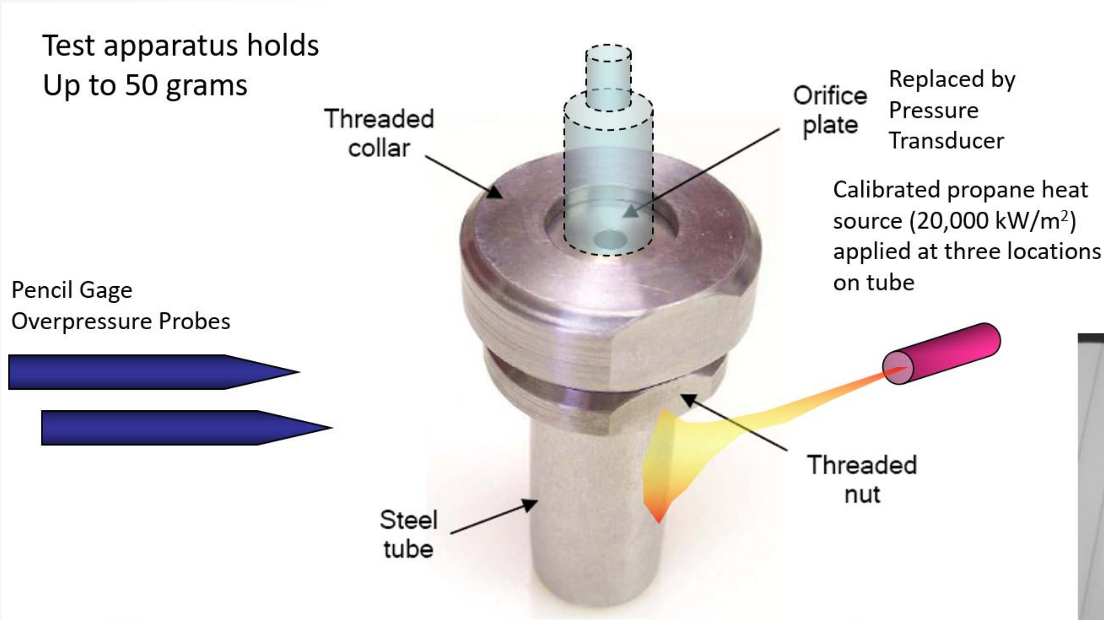
IVM Model **Infrastructure Check**

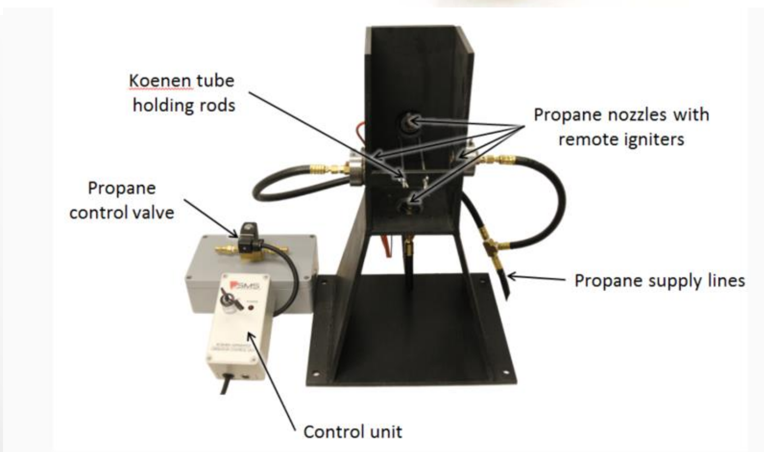
Model Input | Model Infrastructure | Model Output

Is the model infrastructure correctly configured so that the model output can match experimental results with model inputs that are realistic?

Additionally, do realistic changes in model input parameters result in a corresponding expected change in model output?

Koenen Testing for Model Infrastructure Check





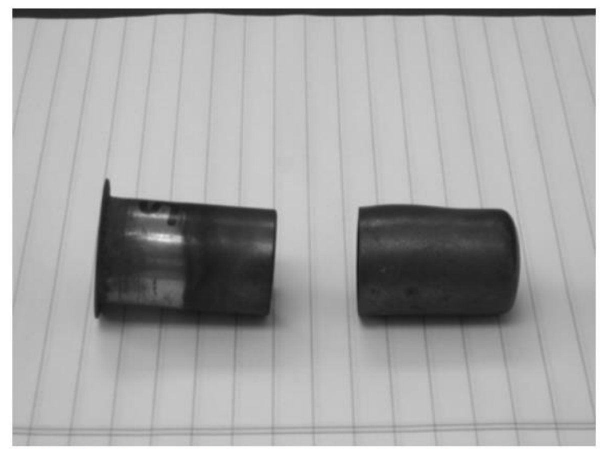


Photo 7: Koenen tube after Trial 4 AORC test with minimum surface area shows minor damage and break at score line.

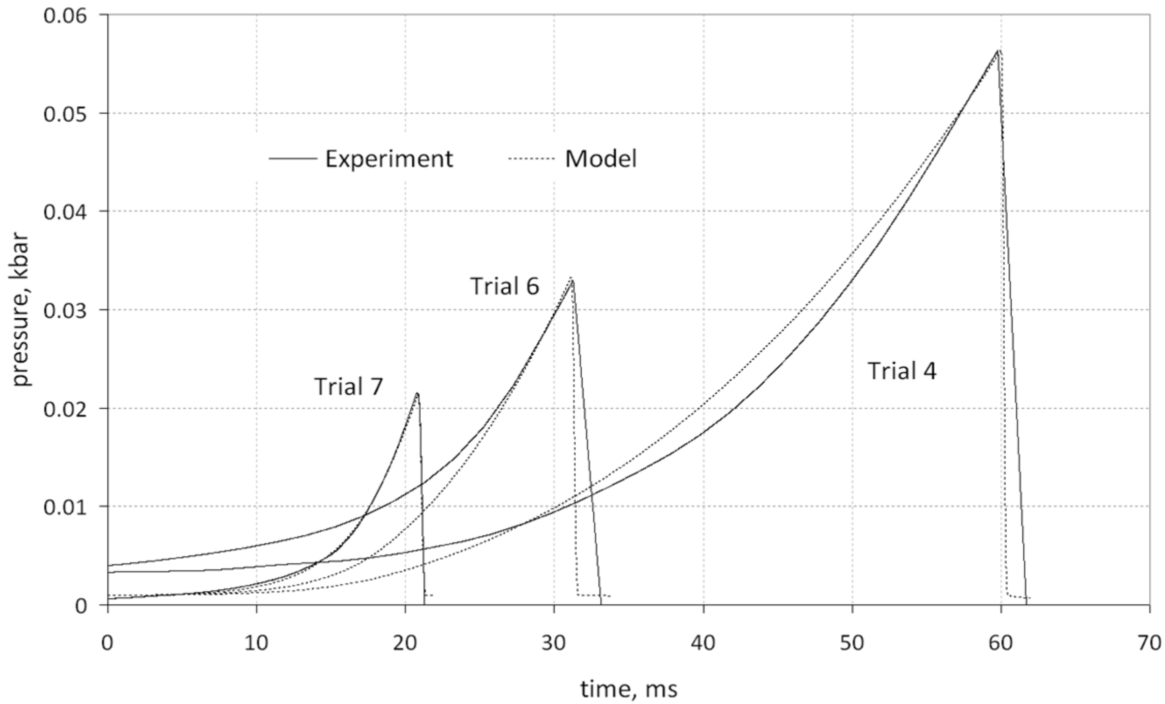
Model Infrastructure Check: Koenen Testing

Table 1. Comparison of Experimental to Model Results for Instrumented Koenen Trials

Material	Trial Mass, g	Trial Surface Area, cm^2	Trial #	Max P, bar*	Max P (Model), bar*	Max dP/dt, kbar/s*	Max dP/dt (Model), kbar/s*	Overpressure, psi†	Overpressure (Model), psi†	Fragment Velocity, ft/s	Fragment Velocity (Model), ft/s‡
Model Rocket Propellant	33.51	54.0	1	Instrument saturated	328	Instrument saturated	135	4.48, 4.18	4.43, 4.00	Tube fragmented	389 (328)
	17.84	26.0	2	Instrument saturated	328	Instrument saturated	46.7	>0.416, >0.380	5.72, 5.13	Tube fragmented	447 (411)
AORC Propellant	2.02	13.8	3	53.1	52.7	2.30	2.29	>0.304, >0.296	2.62, 2.39	Tube didn't fully separate from base	138 (191)
	1.60	13.7	4	56.3	56.4	2.56	2.35	>0.544, >0.526	2.71, 2.48	249 ± 34	145 (198)
	2.25	27.2	5	60.7	61.0	6.17	4.94	>0.436, >0.369	2.80, 2.56	252 ± 21	152 (205)
	2.23	26.1	6	33.0	33.3	2.73	3.31	>0.383, >0.302	2.11, 1.93	151 ± 15	101 (151)
	3.77	43.6	7	21.6	21.4	5.52	4.34	1.13, 1.05	1.70, 1.57	129 ± 16	74.9 (119)
	4.61	56.1	8	73.1	73.2	7.52	11.9	>0.583, >0.365	3.00, 2.73	170 ± ? (Tube impacted side of Koenen)	171 (220)

See Final Report for Further Details: Contract N68335-10-C0452 (SMS-2426) "Prediction of the Full-Scale Cook-off Response Based on Small-Scale Testing," February 28, 2011

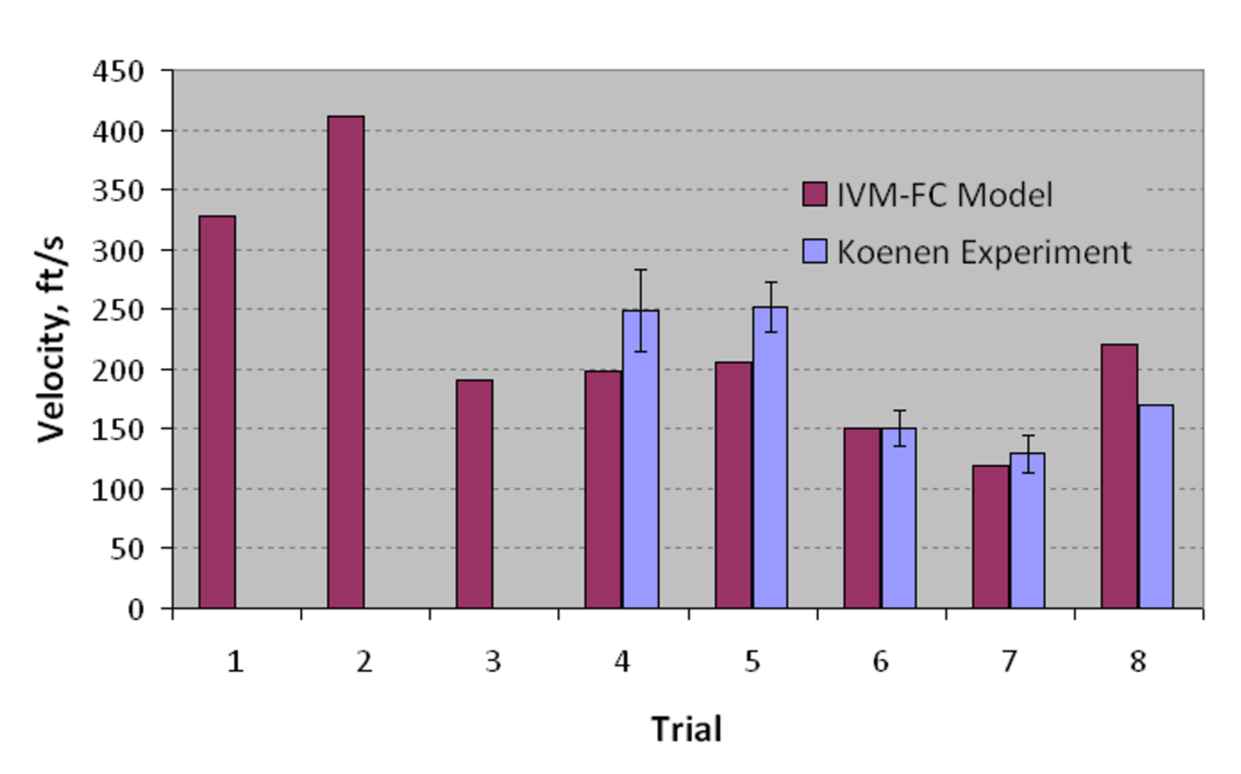
Model Infrastructure Check: Koenen Internal Pressure Results



- IVM Inputs changed to yield Trial 7 experimental result
- Same inputs used for Trial 4 and 6

See Final Report for Further Details: Contract N68335-10-C0452 (SMS-2426) “Prediction of the Full-Scale Cook-off Response Based on Small-Scale Testing,” February 28, 2011

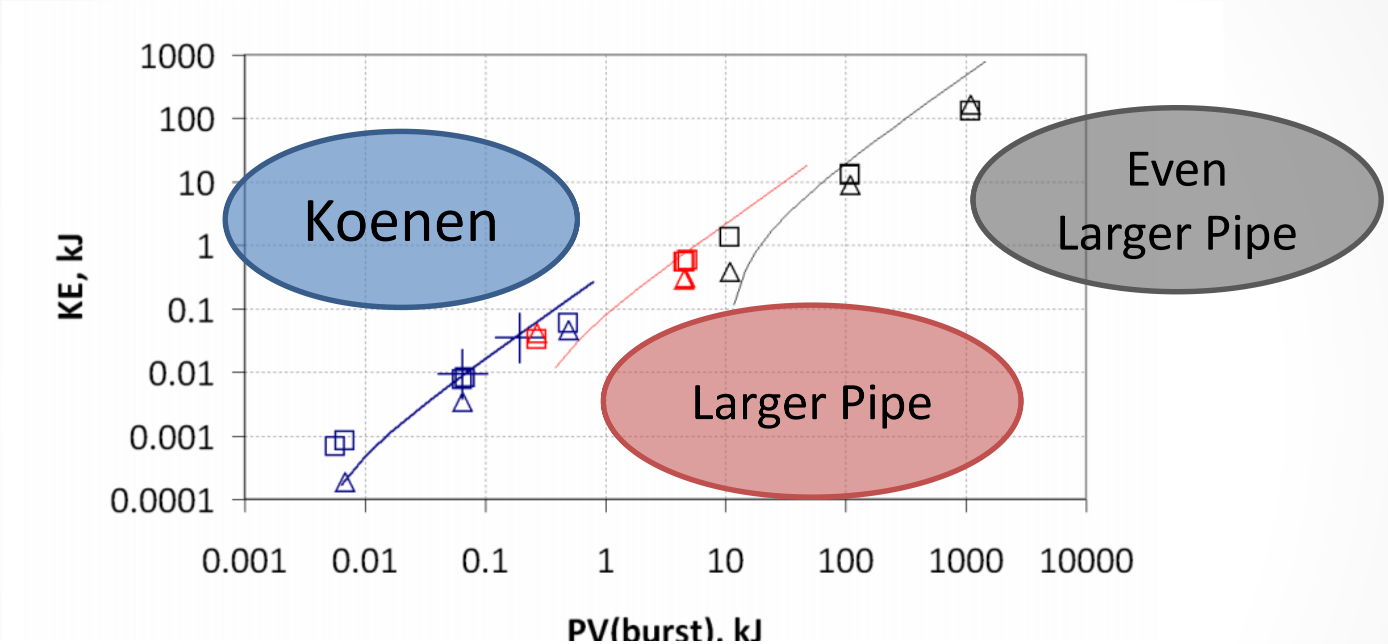
Model Infrastructure Check: Fragmentation



- Experimental pressure burst value used in prediction of fragment velocity in addition to solving the equations of motion to yield the max velocity

See Final Report for Further Details: Contract N68335-10-C0452 (SMS-2426) "Prediction of the Full-Scale Cook-off Response Based on Small-Scale Testing," February 28, 2011

Model Validation: Scale-up and Fragment Kinetic Energy Prediction



See Final Report for Further Details: Contract N68335-10-C0452 (SMS-2426) "Prediction of the Full-Scale Cook-off Response Based on Small-Scale Testing," February 28, 2011

Lines from Literature: "Disruptive Failure of Pressure Vessels," M.R. Baum, 1987, quoted in Loss Prevention in Process Industries, 2nd Ed, Vol. 2, 1996, pg. 17/213.

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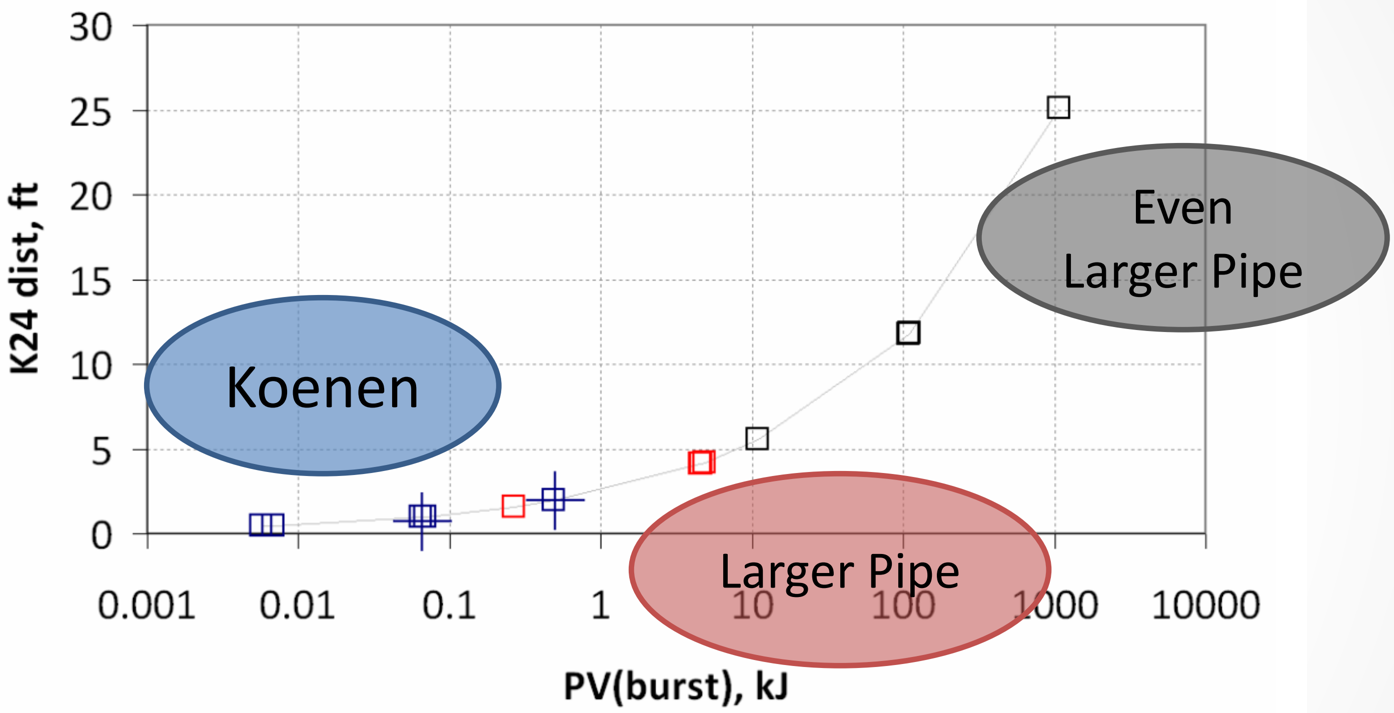
Model Prediction: Overpressure



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MLRS Rocket Motor

Draft

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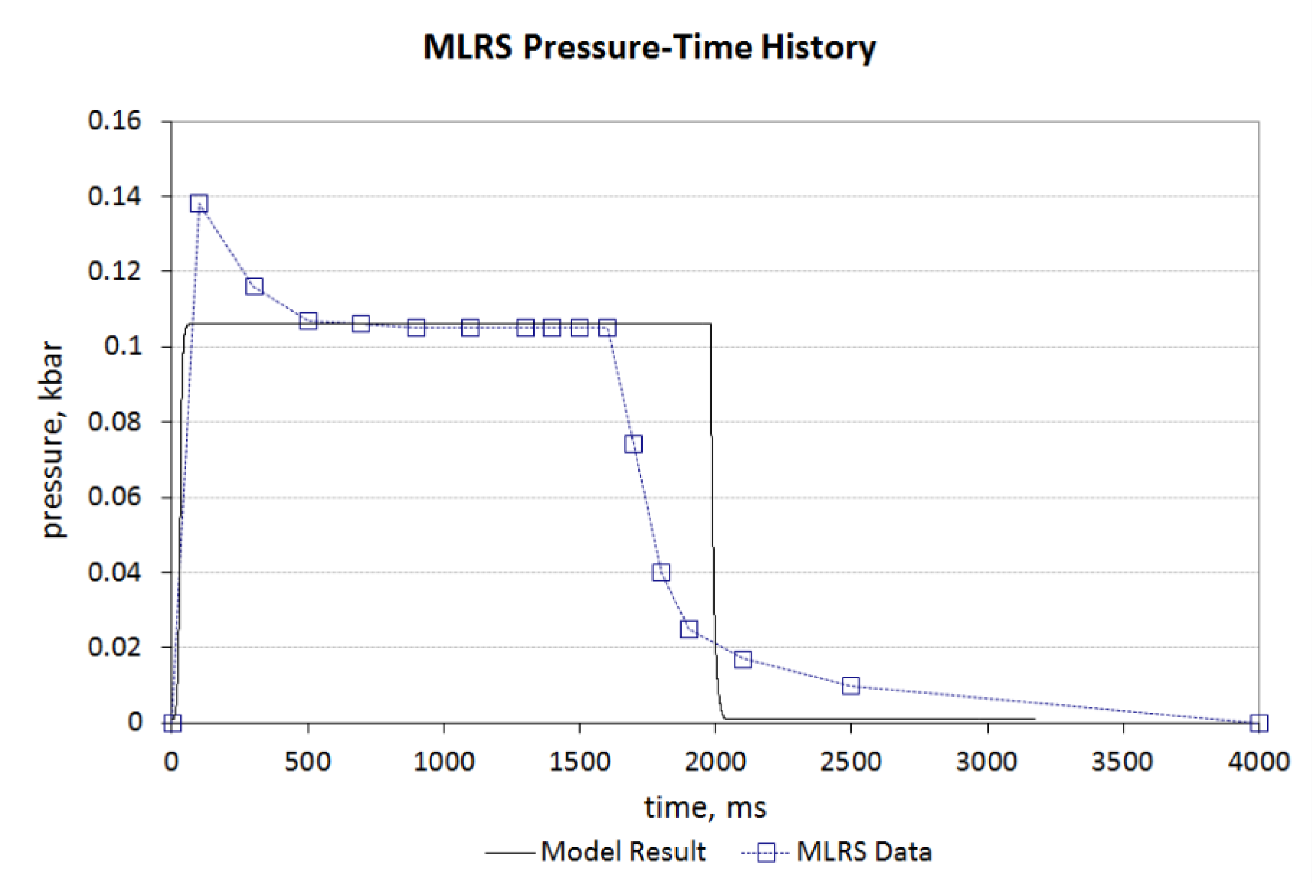
MLRS Rocket Motor:
Model Input Determination-Internal Pressure



- IVM model inputs changed to match the internal pressure

MLRS Firing in Large Vessel: Model Validation

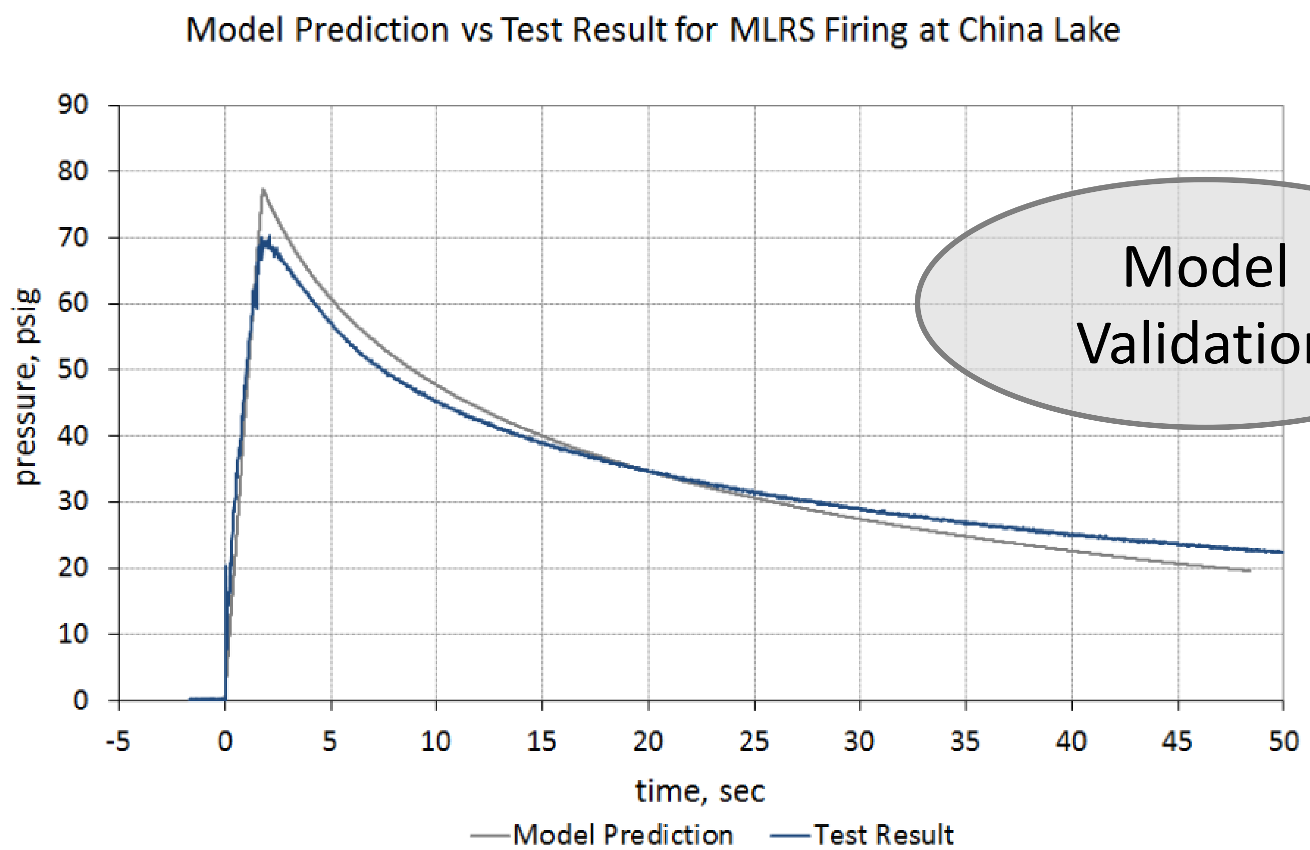


Figure 4: Model prediction versus the test result for an MLRS firing at China Lake inside a large vessel.

Model Validation

Examples of IVM Application for Burning/Deflagration Reactions

- Koenen Testing and Model Prediction (2426*, 5100**)
- MLRS and other Motor Firings in Large Chamber (2617, 2664*, 2851, 2900, 3130)
- Australian Propellant Dryer Modeling (3295)
- Ribbon blender violence outcome (3380*)
- Smokeless powder bulk bag modeling with test data (3486)
- Venting area estimate for metallic dust (4675A, 4791B**)
- Determination of combustion compositions in a furnace (4347B)
- Venting calculations for ejection seats motors (4371, 4566)
- Small Arms Manufacturer
  - Priming bowl detonation and burn (4725)
  - Priming shield (4887)
  - Smokeless powder drum venting calculation (4583)
  - Smokeless powder initiation in a hopper with stack (4700)
- Fragment velocity estimates from a pressurized chamber burst (4872)
- Venting area estimate for a vented concrete structure from a rocket motor (4765)
- Determining if additional vent area is required for a warehouse from burning of smokeless powder (4802)
- Critical height testing (5100**)
- **M1 Propellant Combustion in Vented Concrete Vault (4923*)**

*Validated
**To be validated

TM 8742 Kasun Structure Testing & Modeling

FIGURE I-7. Test Structure With Plate Having a 79-cm Orifice Bolted Into Place.

Table 1: Experimental Setup in 2m x 2m x 2m Kasun Reinforced Concrete Structure

Test	Propellant Type	Mass, lb	Drums	Initial Vent Dia., cm
1	1P	296	3	79
2	1P	1176	8	39
3	7P	264	3	79
4	7P	1108	8	39

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pound of smokele

FIGURE I-6. Three Drums of M1 Propellant Placed Within the Structure for Test 1.

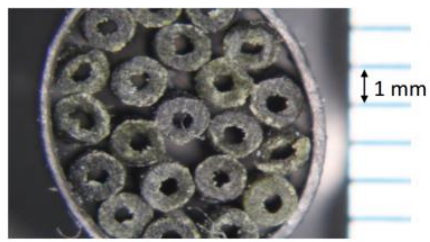

FIGURE I-2. End View of M1 Gun Propellant Grains Used in Tests 1 and 2.

Grains Used in Tests 1 and 2.

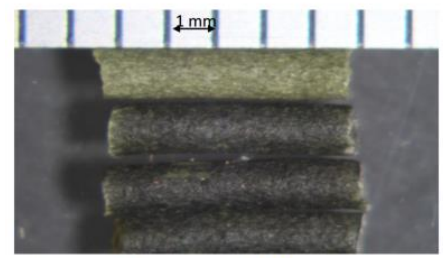

FIGURE I-3. Side View of Propellant M1 Gun Propellant Grains.

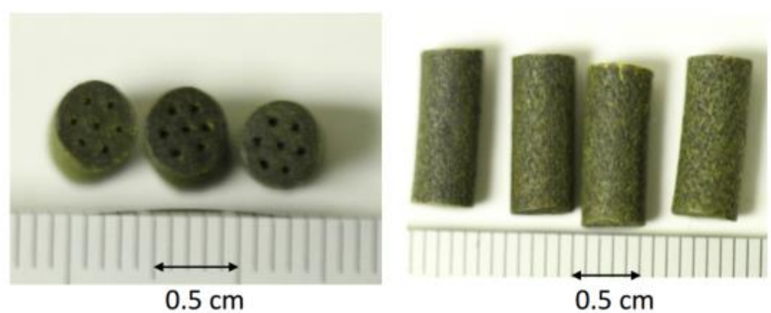

FIGURE I-4. M1 Propellant Grains Used in Tests 3 and 4.

IVM Prediction of Kasun Structure Tests

- All IVM Parameters obtained from literature
- IVM Parameters highlighted in following slides
- Blind IVM Predictions are then highlighted
- Comparison to experimental results then presented

IVM Parameters (from Literature): Burn rate

- One of the most critical factors is the propellant burn rate
- The atmospheric burn rate for each M1 propellant type was calculated as follows:
  - **The burn rate per surface area as calculated from the literature** (112 kg of M1 propellant burns in 18 square foot pan in 17 seconds) [See "Controlled expedient disposal of excess gun propellant," M.R. Walsh, S. Thiboutot, M.E. Walsh, and G. Ampleman, US Army Research Paper 232 (2012)] is equal to 3.94 kg/s/m2. With a barrel cross sectional area of 0.193 m2, **the top-down burn rate in the barrel of one of the propellant types is then 0.759 kg/s (1.67 lb/s). That burn rate is assumed to be the slowest of the two types**.
  - Then calculating the surface area per pellet (based on grain geometry), and the number of pellets in each barrel (based on the bulk density of 1P: 762 kg/m^3, 7P: 543 kg/m^3 and a solid density of 1569 kg/m^3); combined with the propellant depth in the barrel, the surface area per depth is (1P: 567.4 m2/m, 7P: 112.42 m2/m). **Or in other words, there is 5 times the exposed surface area for the single perforation propellant than the multi-perforation M1 propellant**
  - **Atmospheric burn rates is calculated as 0.759 kg/s (1.67 lb/s) for the multi-perforation propellant and 3.83 kg/s (8.45 lb/s) for the single perforation propellant**

IVM Parameters (from Literature)

- Propellant burn pressure exponent is 0.7 (based on literature for smokeless powder)
- Assumed 39 mol of gases generated for each kg of propellant burned (typical for smokeless powder)
- Temperature of combustion gases: 2400 K which is a literature based estimate for M1 propellant
- Fraction of combustion gases that can participate in afterburning (based on Cheetah calc for nitrocellulose): 0.3
- Included afterburning of combustion gases with oxygen present initially in the structure
- Used 4 different gases in structure: inert (CO2), reactive (CO), oxidative (O2), and water (H2O)

IVM Parameters (from Literature) cont.

- Impulse and pressure at which structure fails estimated from literature (40 psi and >2 psi-s) for reinforced concrete sheer walls

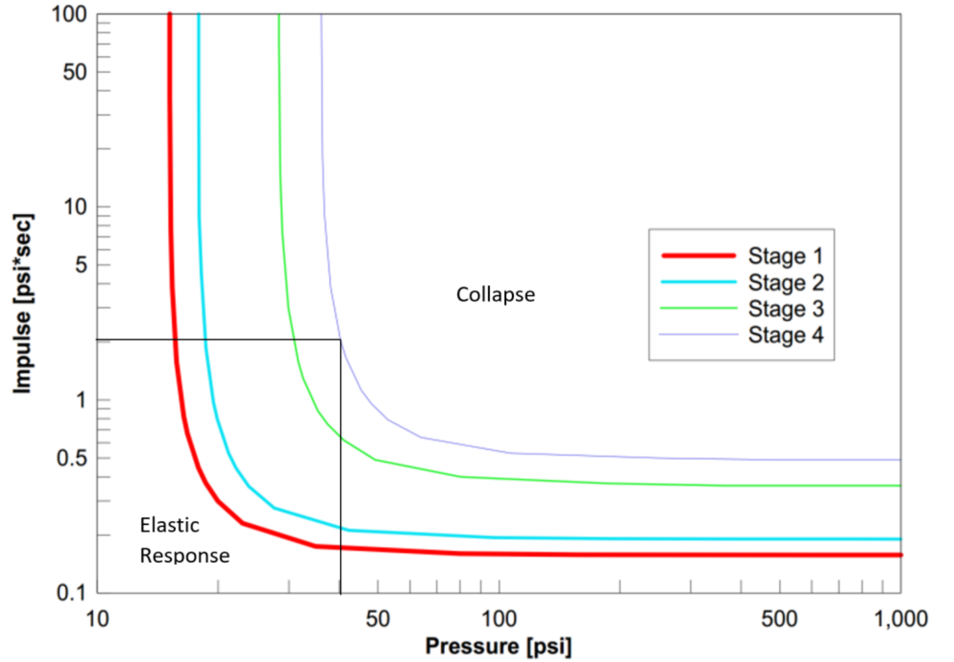

Figure 46: Pressure vs. Impulse Curve (System Model)

From K. Wheaton, and C. Naito, "Blast Assessment of Load Bearing Reinforced Concrete Shear Walls," April 2005, Lehigh University Lehigh Preserve, ATLSS Report No 05-08.

IVM Predictions: Violence Outcome

Trial 1 & 3: **Burn Predicted**

FIGURE I-6. Three Drums of M1 Propellant Placed Within the Structure for Test 1.

FIGURE I-7. Test Structure With Plate Having a 79-cm Orifice Bolted Into Place.

Trial 2 & 4: **Explosion Predicted**

FIGURE V-1. Test 4 Structure With M1 Propellant Filled Barrels.

FIGURE I-16. Exterior of Kasun Structure.

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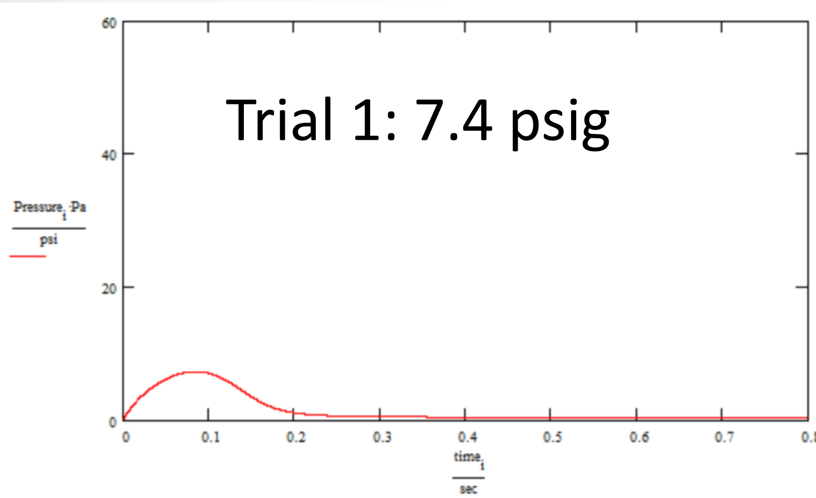
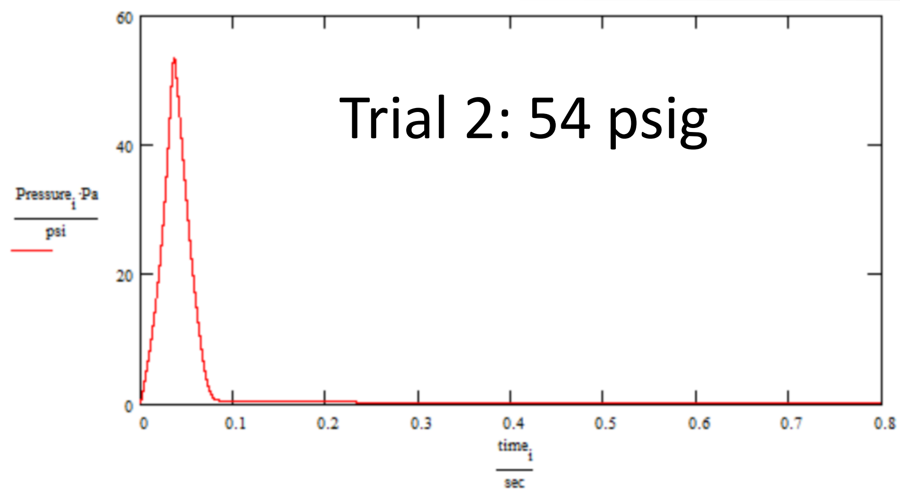
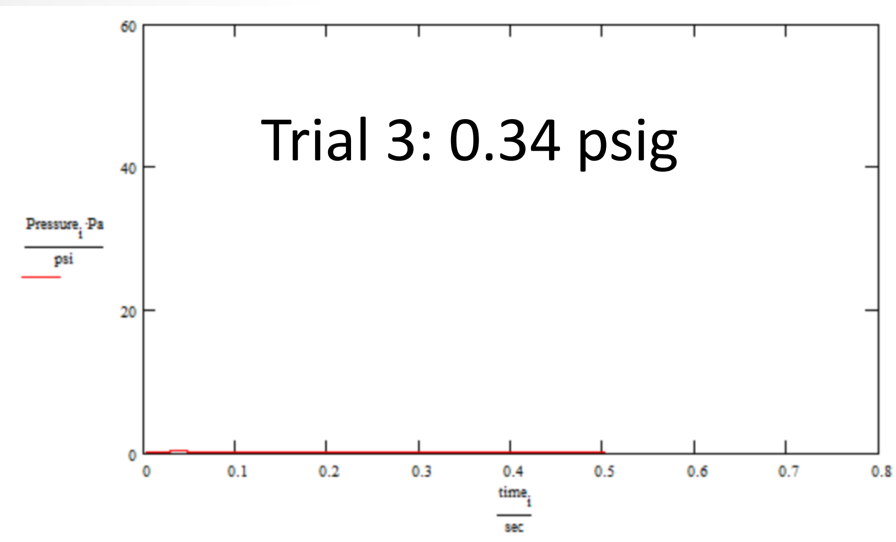
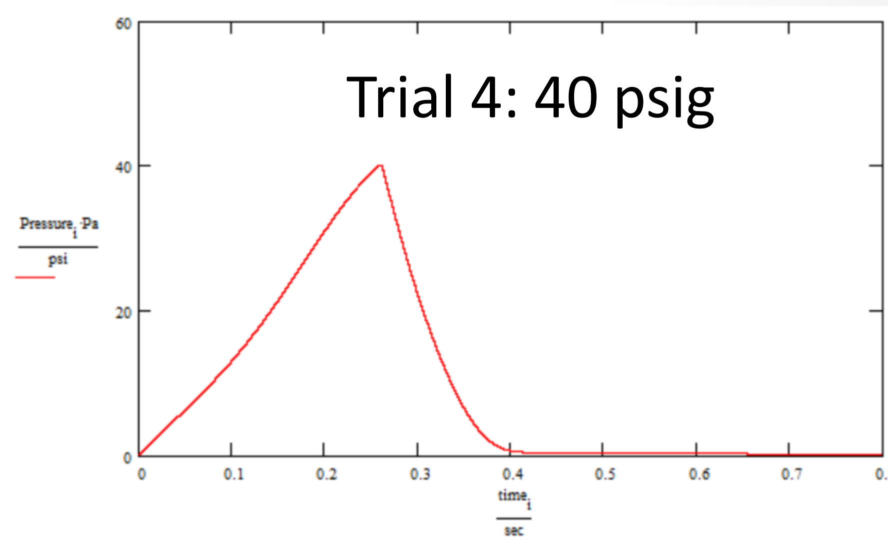
IVM Predictions: Max Internal Pressure









Blind IVM Prediction & Experimental Results

	Violence Outcome		Max Pressure, psig		Impulse, psi-s	
Trial	Model	Experiment	Model	Experiment	Model	Experiment
1	Burn	Burn	7.4	<2	-	-
2	Explosion	Explosion	54	47	2	5
3	Burn	Burn	0.34	<2	-	-
4	Explosion	Explosion	40	34	7.2	5

Experimental Results in "Combustion of Hazard Division 1.3 M1 Gun Propellant in a Reinforced Concrete Structure," A. Farmer, K. Ford, T. Boggs, A. Atwood, and J. Covino, NAWCWD TM 8742, (2015).

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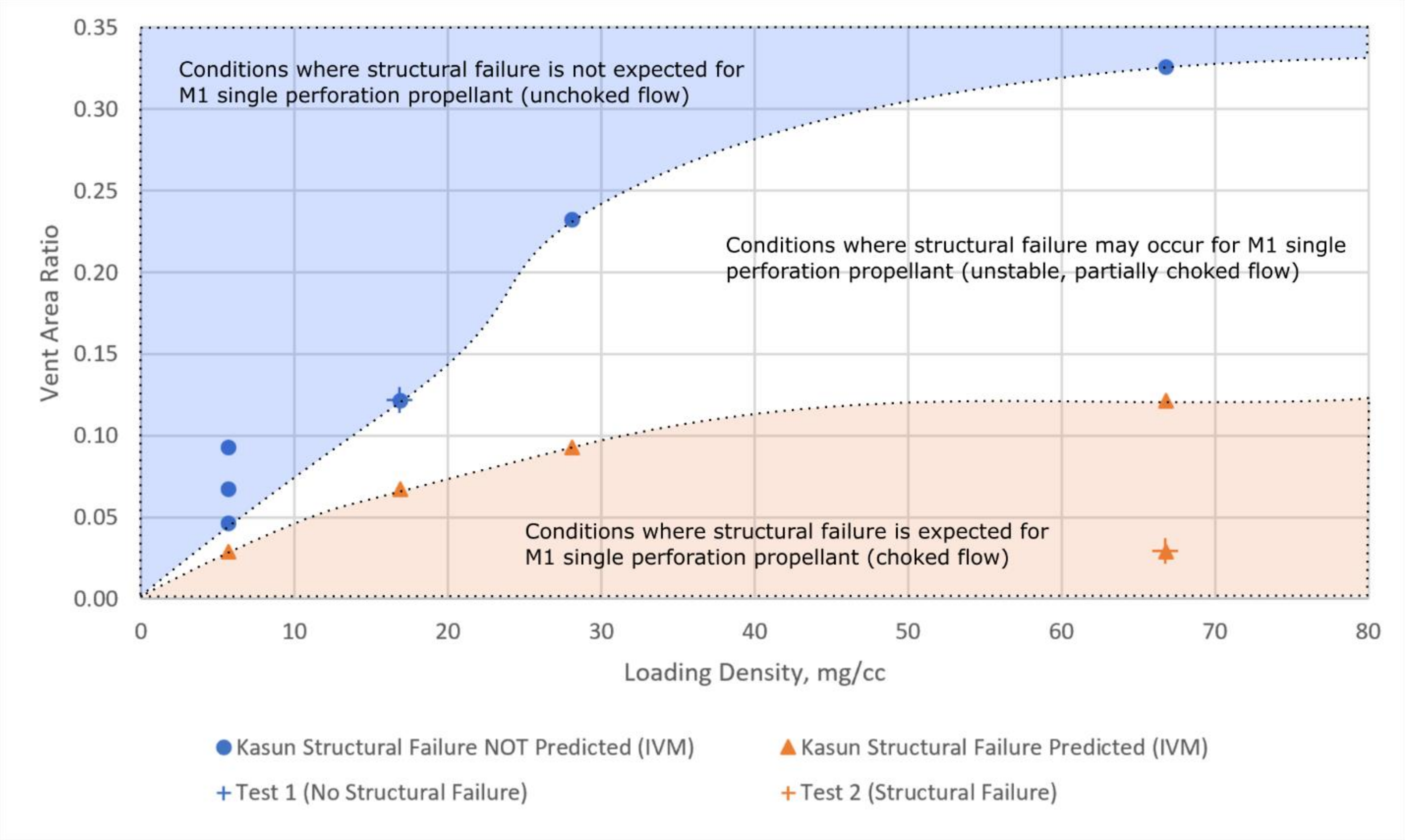
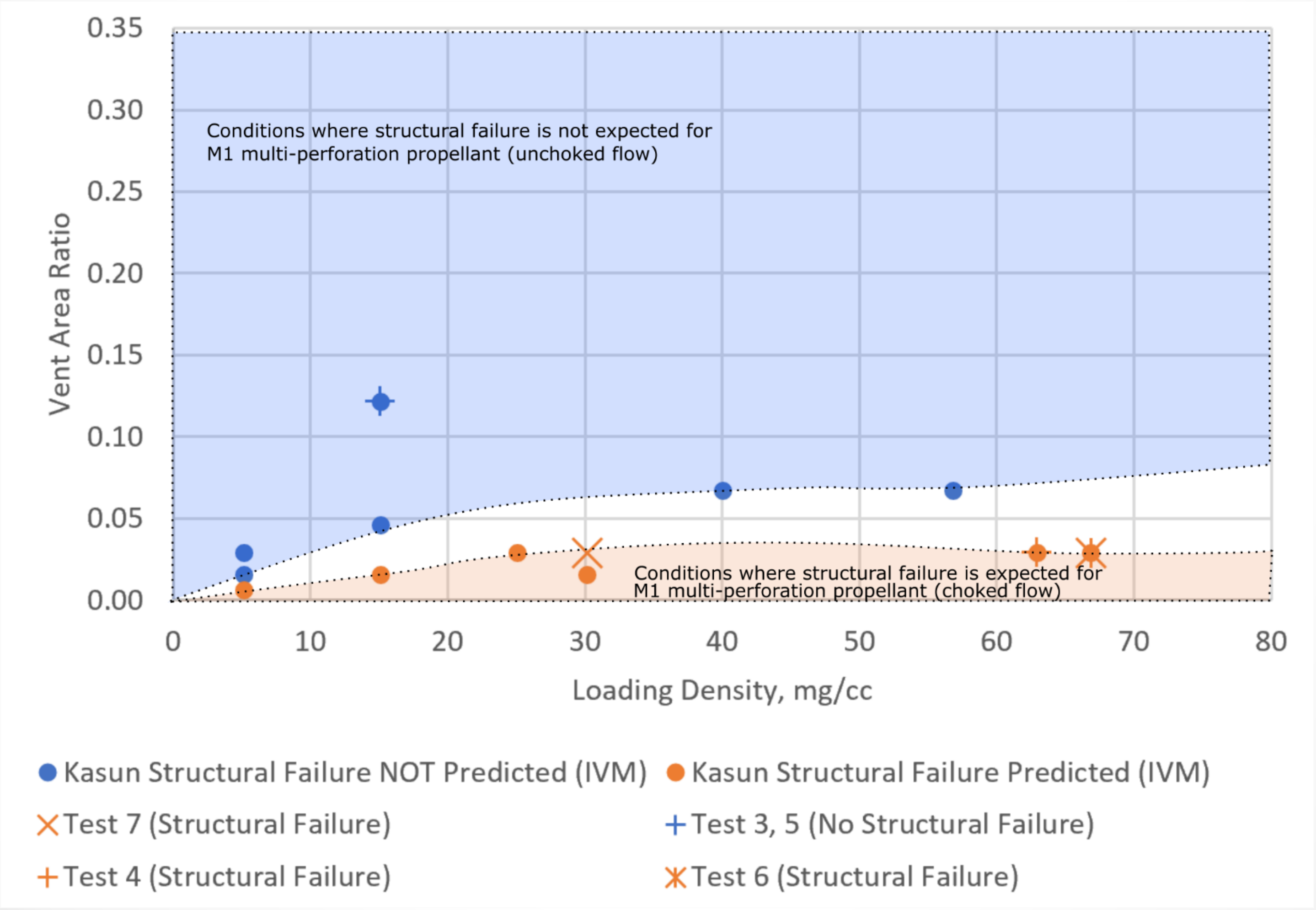
Vent Area Ratio and Loading Density for Single Perforation M1 Propellant



Vent Area Ratio and Loading Density for Multi Perforation M1 Propellant



Summary

- An effective model requires appropriate model inputs, model infrastructure, and model outputs
- The IVM method is NOT a “one size fits all” approach
  - Model Infrastructure must be adjusted to accurately reflect the unique and varied conditions/scenarios encountered.
- The Integrated Violence Model (IVM) infrastructure has been checked with multiple applications.
- IVM has been **validated** for several scenarios including to determine the needed vent area to prevent a deflagration event
- Application of IVM is on a case-by-case basis and improvement in methodology can occur