SAND2015-10817PE

COMBATING TERRORISM TECHNICAL SUPPORT OFFICE

Explosive Testing and Blast Modeling Summit
16 December 2015

CTH, Sierra/SM and Zapotec–Sandia National Laboratories

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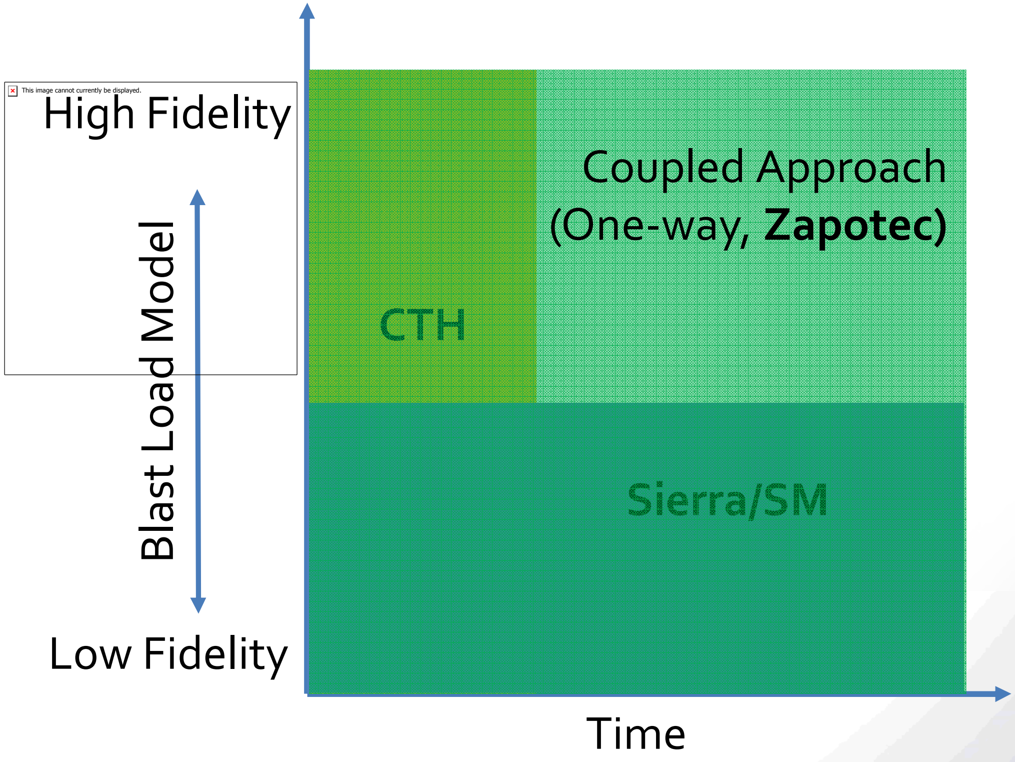
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Tool Description

Sandia National Laboratories' (SNL) Engineering Sciences Center maintains and utilizes three tools for the modeling and simulation of blast:

- **CTH** – a parallel Eulerian shock-physics code
- **Sierra/SM -** a parallel nonlinear Lagrangian solid mechanics code
- **Zapotec –** a two way coupling code between CTH and Sierra/SM



Blast/Structure Code Regimes

CTH (Eulerian):

Blast Load:
Captures ***complex*** shock (pressure) behavior (detonation product equation of state, reactive flow models, etc.)

Structure Behavior:
Very large deformation (phase change/gas flow), surfaces less well defined, high resolution may be required, limited to ***early time*** structural response

Problems that fit into multiple regimes require a coupled approach

Sierra/SM (Lagrangian):

Blast Load:
Simplified blast methods (e.g. CONWEP); misses pressure wave reflections and complexity of near field blasts

Structure Behavior:
Large deformation, failure & fracture captured at ***longer time*** scale, non-linear (geometry and material response), multi-physics solutions (thermal/ mechanical, thermal/fluid and fluid/structure)

Blast/Structure Code Regimes

CTH :

<u>**Blast Load**</u>: Captures ***complex*** shock (pressure) behavior (detonation product equation of state, reactive flow models, etc.)

One-Way Coupling

General approach: Use tracers to harvest information from CTH, then apply to Lagrangian structure

- Time-consuming for analyst, but straightforward (and fast) simulation
- Great for single CTH simulation, many Lagrangian simulations
- Capture reflected pressure of initial geometry
- Limitations: misses effects of geometric change, spatial resolution typically low

Sierra/SM:

Structure Behavior: Large deformation, failure & fracture captured at ***longer time*** scale

Blast/Structure Code Regimes

CTH :

<u>Blast Load</u>: Captures ***complex*** shock (pressure) behavior (detonation product equation of state, reactive flow models, etc.)

Zapotec (Two-Way Coupling)

General approach: Deformed finite element mesh from Sierra/SM inserted into CTH; updated at each time step

- Captures effect of deformed structure on blast loading
- Eroded Lagrangian elements can be "donated" to CTH to preserve mass/momentum
- User controlled coupled materials and time frame

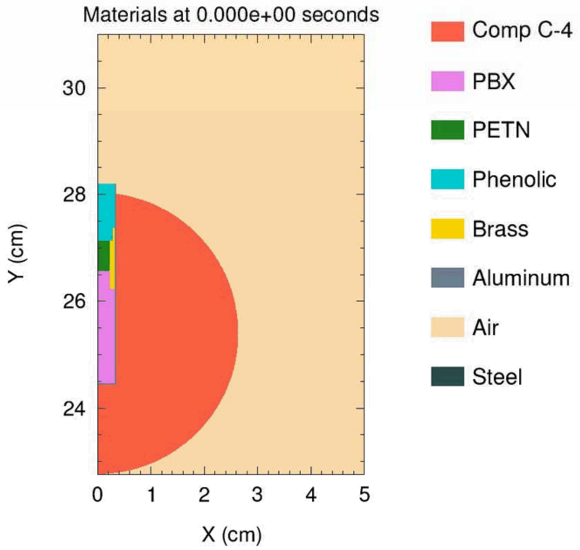
Sierra/SM:

Structure Behavior: Large deformation, failure & fracture captured at ***longer time*** scale

CTH Example: Kinetic Plate

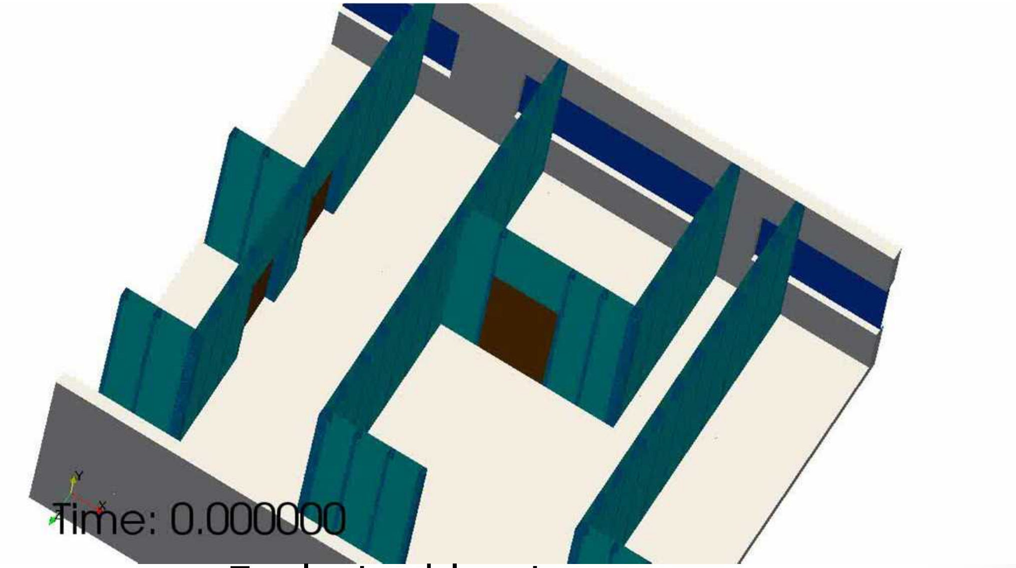
- Experiment:
  - Explosive charge 6” from plate
  - C4 sphere initiated with a RP-83 exploding bridge wire (EBW) detonator
  - Photonic Doppler Velocimetry (PDV) probes measure plate velocity

- Simulation Results:
  - ***Detonator details*** matter (velocities could vary by as much as 23%)
  - Detonator ***placement*** was also a factor
  - Mesh resolution requirements greater than expected for the C4



Sierra/SM Example: Blast in Room

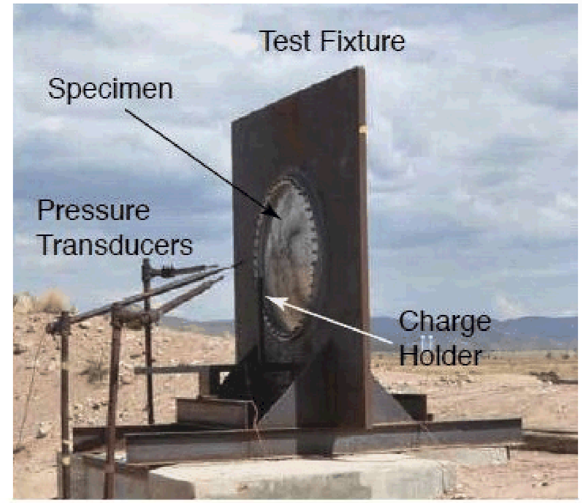
- ConWep blast loading in Sierra/SM (https://conwep.erdc.usace.army.mil/)
- Benefits: Easy & fast
- Can be a great tool for cursory investigation
- Or as the primary tool for problems were ConWep assumptions are valid (spherical or hemi-spherical air blast, wave interactions not important)

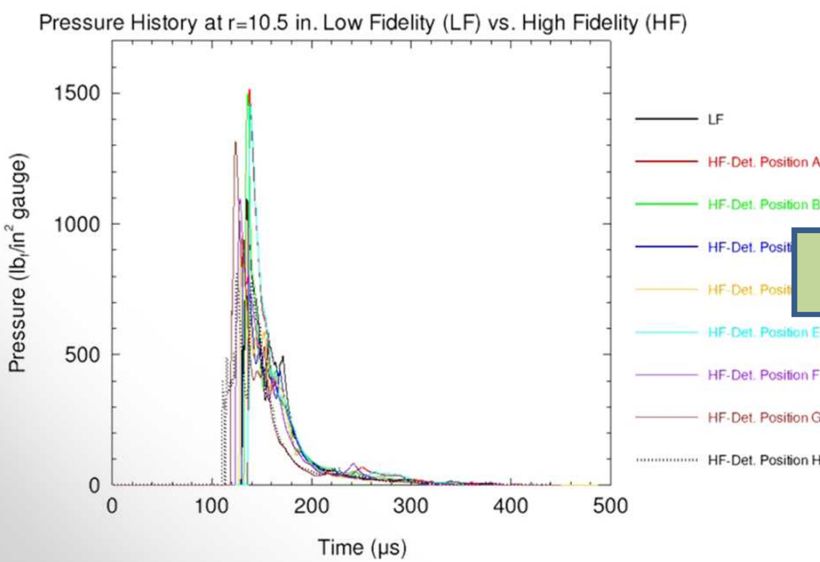


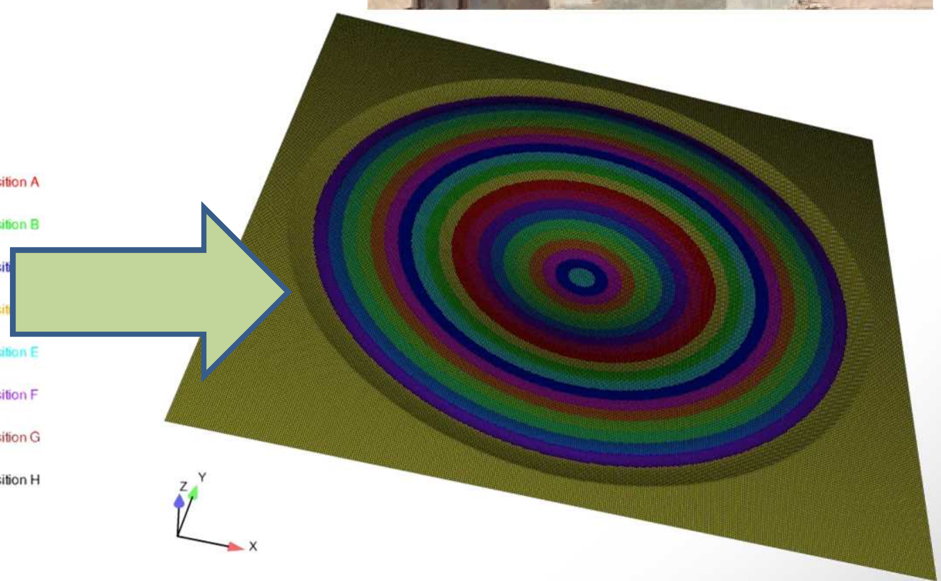
Explosive blast in a room

One Way Coupling: BPV

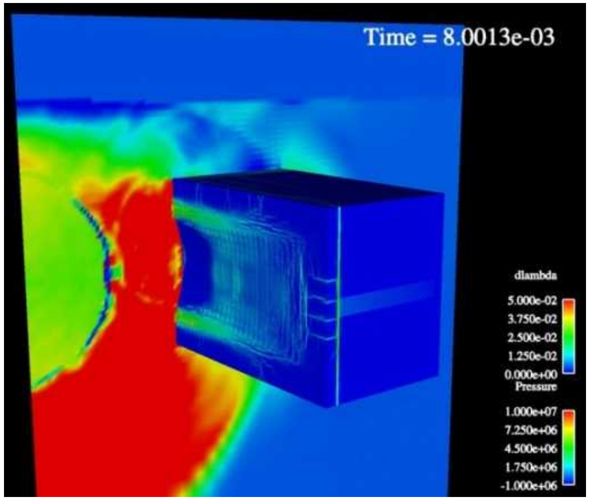
- Blast Plate Validation (BPV) Experiment
  - Comp C4 spherical charge detonated with RP-83 detonator
  - Digital image correlation deflection data and pressure transducers
- Simulation:
  - Harvested pressures from a 2D cylindrical CTH geometry model applied as rings to a 3D circular plate in Sierra/SM



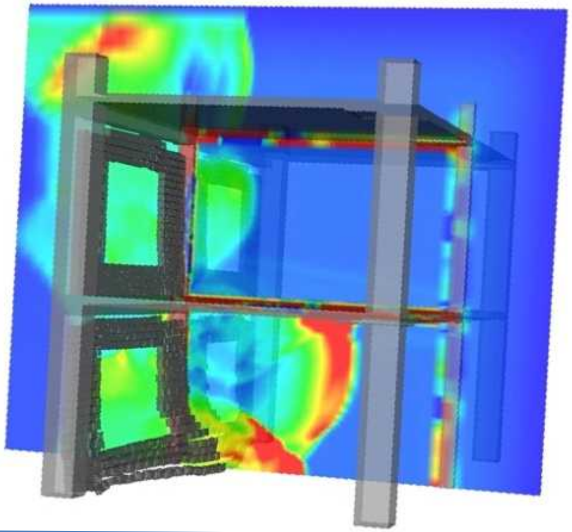




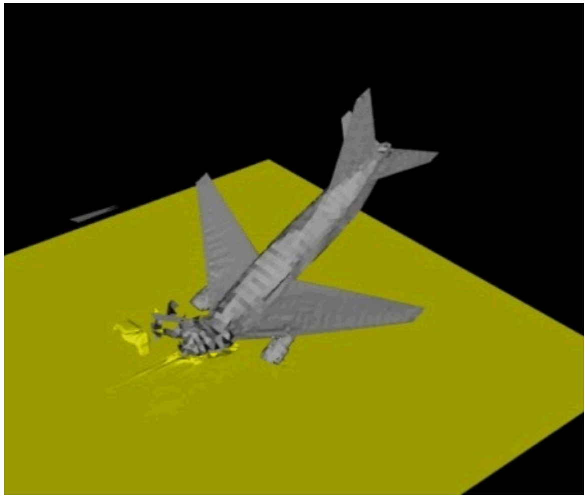
Two Way Coupling: Zapotec



Blast Loading on a Buried Structure



Air Blast on Above Ground Reinforced Concrete Building with Brick Facade



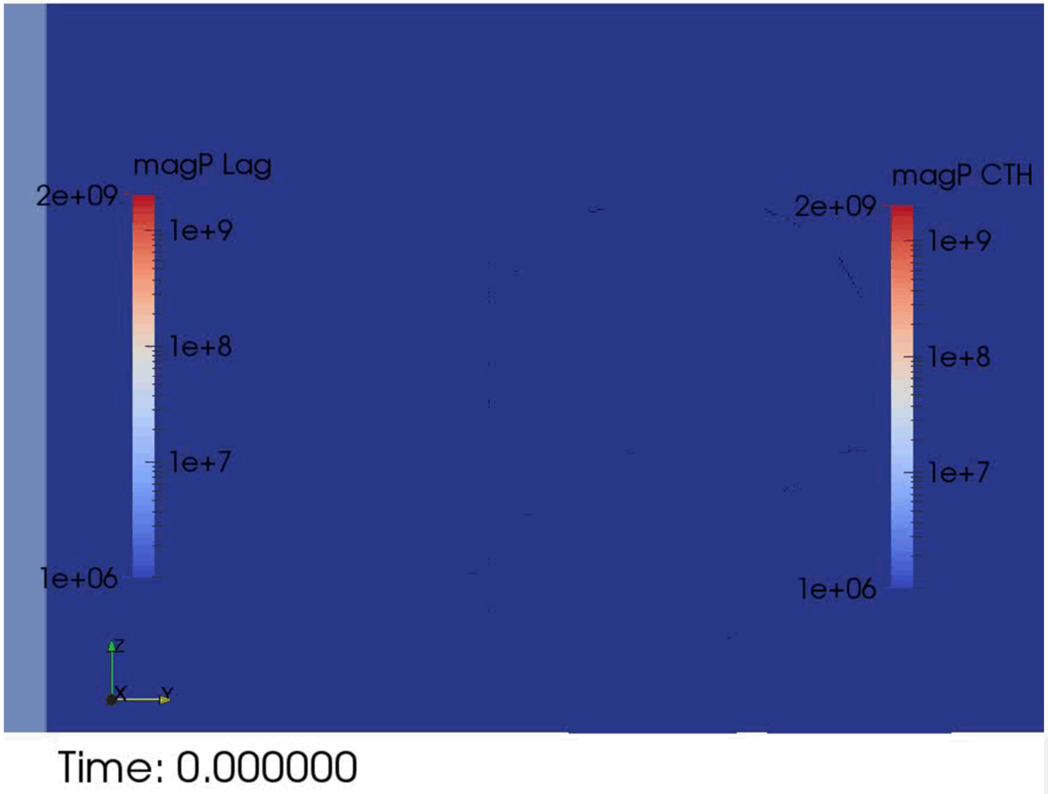
Aircraft Impacts

Zapotec: Blast on Head

Traumatic Brain injury:

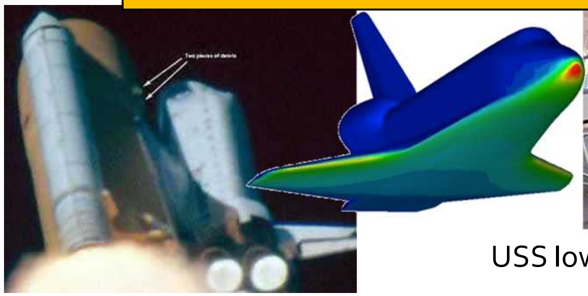
Better understanding of subtle brain injury mechanics and merit assessment of body armor

- CTH
  - Blast
  - Fluids: Blood and cerebrospinal fluid
- Sierra/SM
  - Skull and Brain



High Profile Projects

Accident Investigations

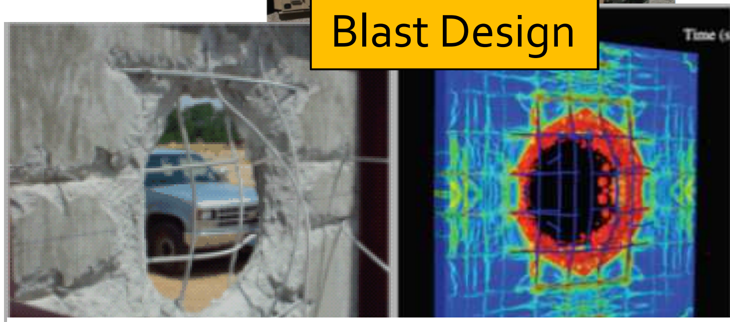


Columbia Space Shuttle Accident (2/4/03)

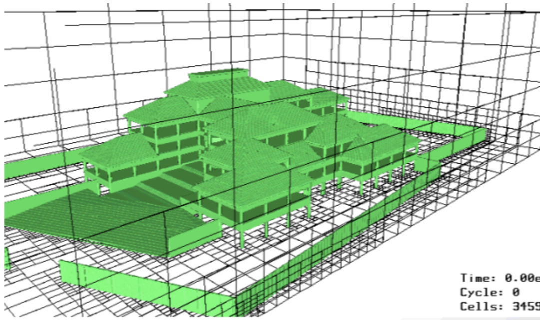
USS Iowa Investigation (4/19/89)

Armored Vehicle Design

Blast Design



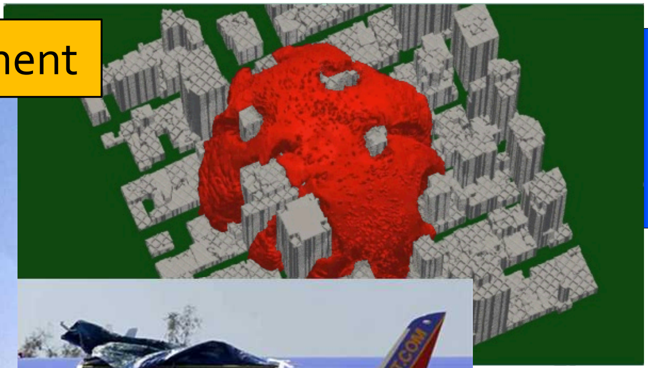
Breaching and breaking/access delay



Building Design (Embassy and Storage Facilities)

Threat Assessment

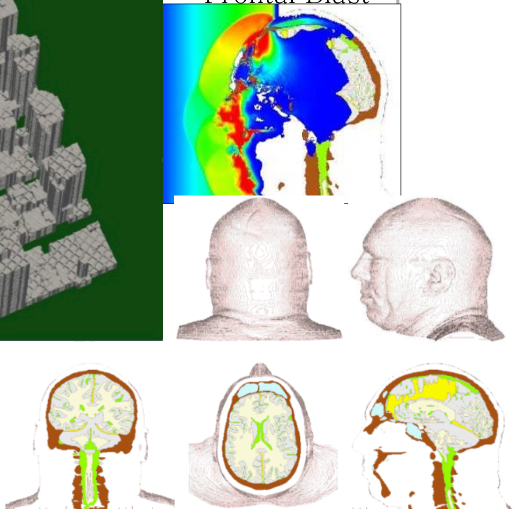
Urban Nuclear Detonation



Post 9/11 Vulnerability Studies (11/11/01)

Aircraft Vulnerability (1/11/13)

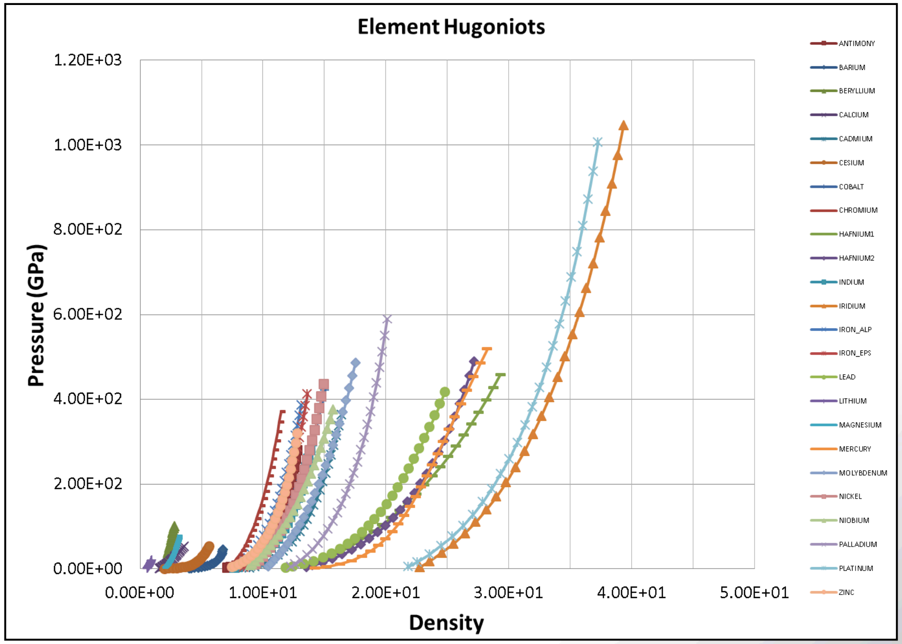
Frontal Blast



Traumatic Brain Injury

CTH Material Database

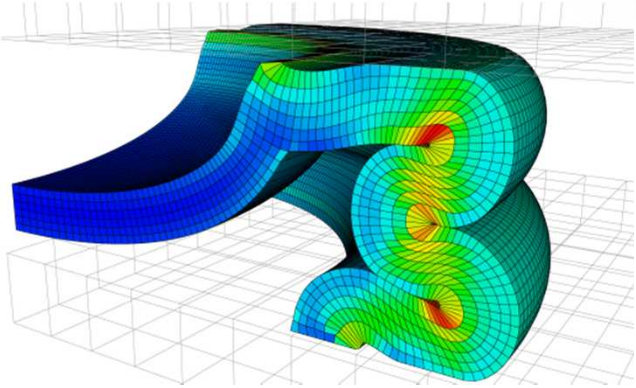
- Explosives:
  - Ideal (TNT, Comp B, RDX, PBX-9501, PBX-9502, etc.)
    - Equation of State (EOS)
      - » Jones Wilkes Lee (JWL) & Sesame Tabular Data
      - » Tiger CTH-Tiger (chemical thermal equilibrium code) can generate a product's EOS if the composition is known
    - Reactive flow models (History Variable Reactive Burn (HVRB), Ignition and Growth, Arrhenius Burn, etc.)
  - Non-ideal (ANFO multiphase model in development) ***current limitation in database***
  - ***Homemade explosives are a limitation*** *(ex. HMTD, ETN, ANAl)*
    - User defined: HP/fuels, chlorate/fuels, etc.
- Inert Materials:
  - Types of materials: metals, plastics, concrete and foams
  - Material behavior features: plasticity, failure and phase changes

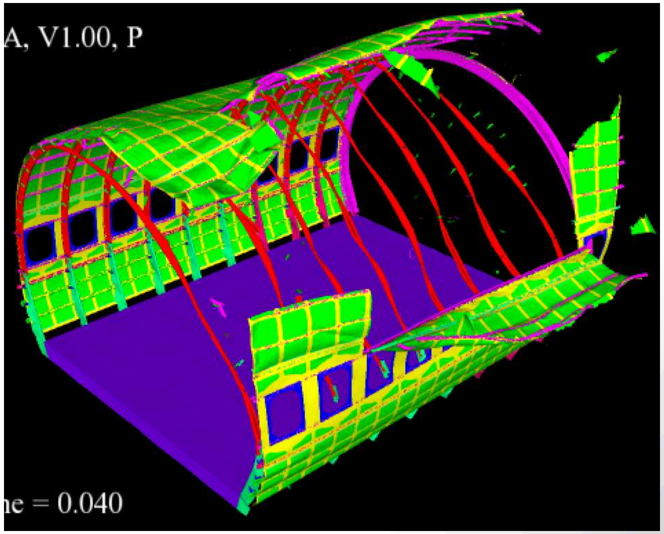


Sierra/SM Material Database

- Lame material library
  - Temperature and strain dependent models
  - Plasticity (power-law hardening, Hill, Johnson-Cook, Bammann–Chiesa–Johnson (BCJ), etc.)
  - Failure (Johnson Cook Damage, multi-linear elastic-plastic with failure, etc.)
  - Specialized materials (foams, plastics, concrete, etc.) ***looking to improve concrete modeling capabilities***
- Has access to the to the CTH Material Model database

Zapotec accesses the Sierra/SM and CTH material models



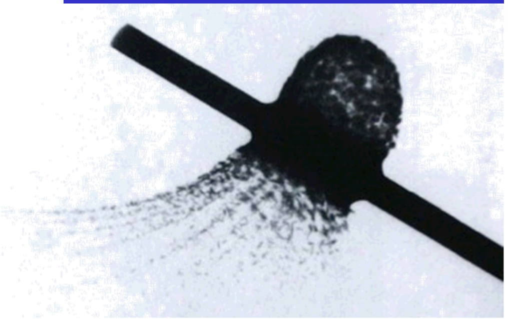


Validation

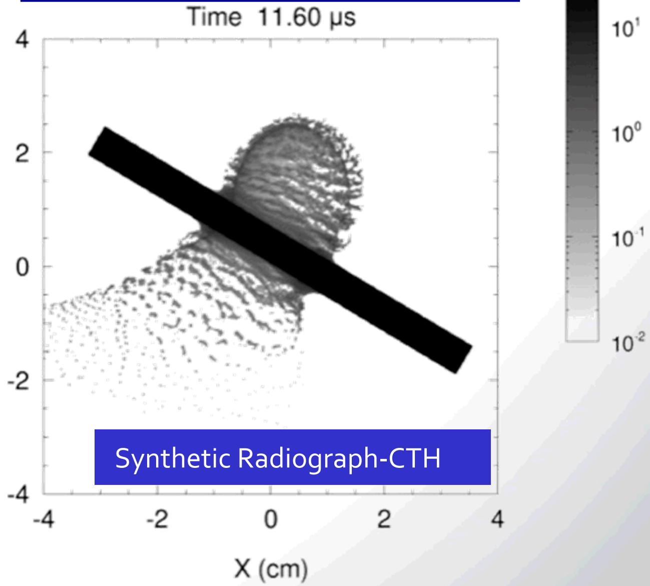
- Sierra/SM
  - Advanced Simulation and Computing (ASC) Program's flagship code for simulation of mechanical systems in the Stockpile Stewardship program.
  - SNL Dept. 1544, Verification and Validation, Uncertainty Quantification and Credibility Processes
- CTH
  - Version 1.0 released in 1987 (Current release version 11.1 June 2015)
  - Thousands of publications showing favorable comparison to data
- Zapotec
  - Validation documentation
  - Future plans to add 50-100 additional problems to test suite

All codes run regression/benchmark suites of problems nightly

Radiograph From Experiment



Re-creation of Grady/Kipp Simulation of Copper Sphere Impacting a Steel Plate (1993)



Tool Planned Updates

New features are continually added to all three codes:

- **CTH:** Adaptive Mesh Refinement (AMR) add in 1999, new reactive flow models, ANFO model production and geometry (diatom) insertion improvements
- **Sierra/SM:** recently added extended finite element method (XFEM), Geomaterial models [Hybrid Elastic Plastic (HEP), Advanced Fundamental Concrete (AFC), High Rate Brittle Concrete model] developed at ERDC will be integrated into Sierra/SM ITAR by FY 2017
- **Zapotec:** currently being updated to interface with the newest version of solid mechanics code (Sierra/SM), beta version to be release FY2016, production version FY2017

All codes moving to next generation platforms (NGP)

A graphical user interface is currently in development, Sandia Analysis Workbench (SAW)

Funding

All three tools are paid for with a combination of DoD and DoE funding:

- CTH is funded through the Joint Munitions Program Technical Group 1 (JMP TCG-I), ASC Integrated Codes (IC), Physics and Engineering Models (P&EM) and Facility Operations and User Support (FOUS)
- Sierra/SM is funded through DOE ASC IC funding
- Zapotec is funded through ASC IC, Missile Defense, JMP TCG-I, and DoD high performance computing management office (HPCMO), HPCMO Application Software Initiative (HASI).

Users

- **CTH & Sierra/SM** licensed to U.S. government agencies and their subcontractors including:
  - DoD Research Laboratories (ARL, ARDEC,AMRDEC, AFRL-RWML, AFTAC, TARDEC, NSWC-DD, NSWC-IH NAWC-CL, ERDC, DoD HPCMO, etc.)
  - DOE facilities (SNL, Pantex, National Security Campus (KCP), etc.)
  - U.S. academic institutions
  - CTH has over a thousand users - Sierra/SM has approximately a hundred users
- **Zapotec:**
  - AMRDEC, ERDC, SNL Dept. 5417 Missile Defense, SNL Dept. 1555 Shock Physics, SNL 6620 Transportation and Org. 5417 Lethality and Threat

System requirements

- **CTH** –Distributed for Linux/Unix, Macintosh and Windows PC
- **Sierra/SM-**Distributed for Linux/Unix and Macintosh
- **Zapotec –** will be distributed at end of FY2017

All three tools are massively parallel

All three tools are available at Army Engineer Research and Development Center DoD Supercomputing Resource Center (ERDC DSRC) and various other DSRC

New Users

Licensing & Training:

- CTH www.sandia.gov/CTH Version 11.1 includes Zapotec II (CTH/Pronto), Export Controlled Information (ECI)/ International Traffic in Arms Regulations (ITAR)
  - POC: Eric Harstad (505) 844-9174 (cth-license@sandia.gov)
  - *Training: annual –* cth-help@sandia.gov
- Sierra/SM : https://sierradist.sandia.gov
  - Version 4.38, Government Use Notice (GUN) required
  - POC: Terri Galpin (505) 845-7949 (tlgalpi@sandia.gov)
  - *Training: biannual (1 internal / 1 external), self-paced training available with emphasis on blast capabilities -* sierra-help@sandia.gov
- Zapotec III (CTH Sierra/SM ITAR coupling)
  - In development (Alpha), will be distributed with Sierra/SM ITAR by the end of FY2017
  - *Training: in the works*

SNL is responsible for updating all the tools

Complex Highly Non-Linear Problems

All tools require ***subject matter expertise*** *(e.g., solid mechanics, shock physics, chemistry, material science, etc.)* and experience in numerical analysis techniques

The three tools provide the flexibility to model the full physics of the system with multiple approaches (CTH only, 1-way couple, Zapotec (2-way couple) and Sierra/SM only):

– Builds confidence in the solution
– Balance model fidelity with finances/time

Sandia's unique core mission as enabled the developed of tools to model extreme events. ***This is an on-going research activity. In the process, of broadening our capabilities to a larger problem space (storage and transportation of nuclear weapons and DoD applications)***

TEST DESCRIPTI

Test Description

- **Test Overview:** Various tests to understand the material behavior under high loading pressures (10-50 GPa). Testing is to develop equation of state.

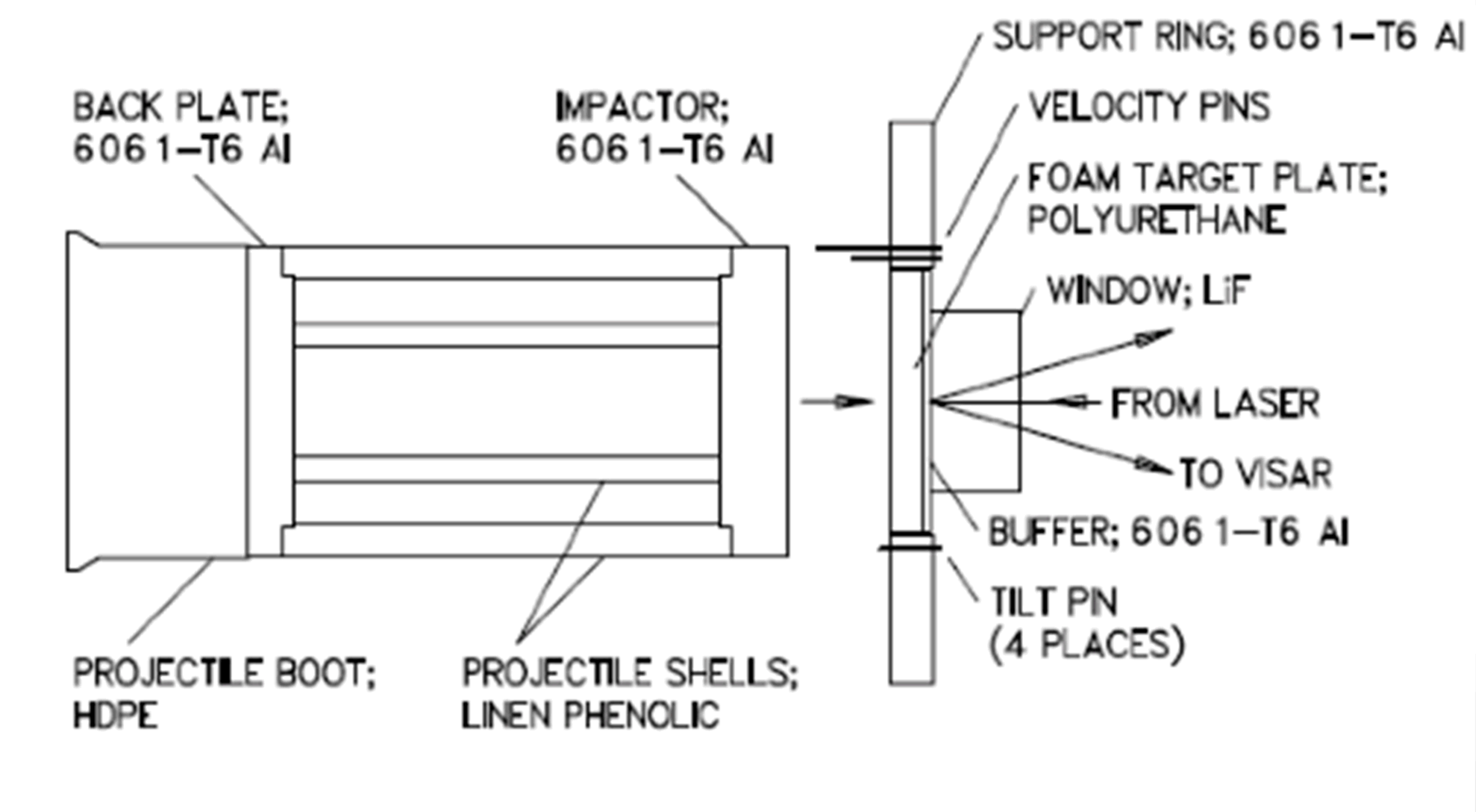
EXPERIMENT TYPES

		Parameters Measured			
Experiment	Abb	Specimen	Standard	Transit Time Instrumentation	Shock Energy Source
Shock and paticle velocities	SP1	U_s, U_D[c]	-	Flash gap and smear camera	HE
	SP2	U_s, U_{proj}[d]	-	Pins and oscilliscope	Propellant driven air gun
	SP3	U_s, U_{proj}[d]	-	Pins, osciliscope, and flash x-ray	ARLG gun
Wedge	WDG	U_s	U_{fs}	Light bomb and smear camera	HE

[a]HE = high explosive
[b]ARLG = accelerated reservoir light-gas gun
[c]U_p = velocity of an explosively accelerated driver plate
[d]Sometimes this projectile s an impedance standard

Marsh, S., LASL Shock Hugoniot Data, University of California Press, 1980.

Test Description – Gun Experiments



Jack Wise, "STAR Experiments", Sandia National Laboratories, 1992.

Test Description

- **Materials Tested:**
  - Elements (e.g. carbon, copper, zinc, etc.)
  - Alloys (e.g. Al 2024, Steel)
  - Minerals and Compounds
  - Rocks and Mixtures of Minerals
  - Plastics
  - Other Synthetics
  - Woods
  - High Explosives, High Explosive Simulants, and Propellants
- **Explosives Tested:**
  - Many ideal explosives
  - Some non-ideal explosives
  - Very few improvised explosives

Marsh, S., LASL Shock Hugoniot Data, University of California Press, 1980.

COPPER

Average ρ_0 = 8.924 g/cm³.

Sound velocities longitudinal 4.76 km/s. shear 2.33 km/s.

References 4, 5, 6, 11, 12, 13, 17

ρ_0 (g/cm³)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm³/g)	ρ (g/cm³)	V/Vo	Exp
8.929	3.927	0.000	0.000	.1120	8.929	1.000	ssp ×
8.920	4.314	.210	8.081	.1067	9.376	.951	iml ○
8.925	4.215	.211	7.938	.1064	9.395	.950	iml ○
8.900	4.217	.223	8.369	.1064	9.397	.947	iml ○
8.928	4.341	.281	10.891	.1048	9.546	.935	iml ○
8.925	4.352	.282	10.953	.1048	9.543	.935	iml ○
8.920	4.321	.286	11.023	.1047	9.552	.934	iml ○
8.920	4.350	.289	11.214	.1047	9.555	.934	iml ○
8.925	4.378	.301	11.761	.1043	9.584	.931	iml ○
8.930	4.303	.302	11.605	.1041	9.604	.930	iml ○
8.930	4.316	.312	12.025	.1039	9.626	.928	iml ○
8.925	4.512	.395	15.906	.1022	9.781	.912	iml ○
8.928	4.501	.398	15.994	.1021	9.794	.912	iml ○
8.930	4.477	.406	16.232	.1018	9.821	.909	spl ⊞
8.925	4.532	.407	16.462	.1020	9.806	.910	iml ○
8.925	4.494	.409	16.405	.1018	9.819	.909	iml ○
8.931	4.566	.413	16.842	.1018	9.819	.910	spl ⊞
8.933	4.471	.434	17.334	.1011	9.893	.903	iml ○
8.933	4.501	.439	17.651	.1010	9.898	.902	iml ○

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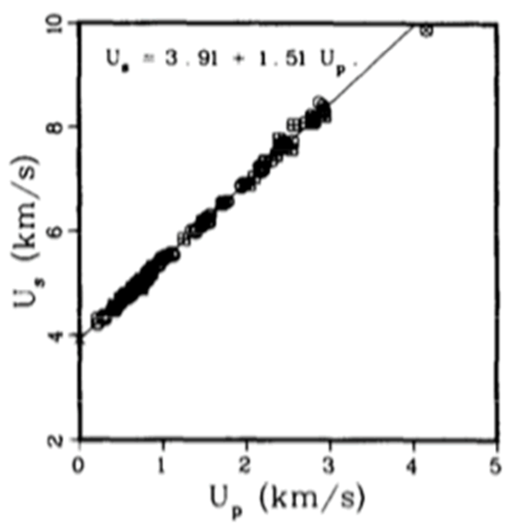
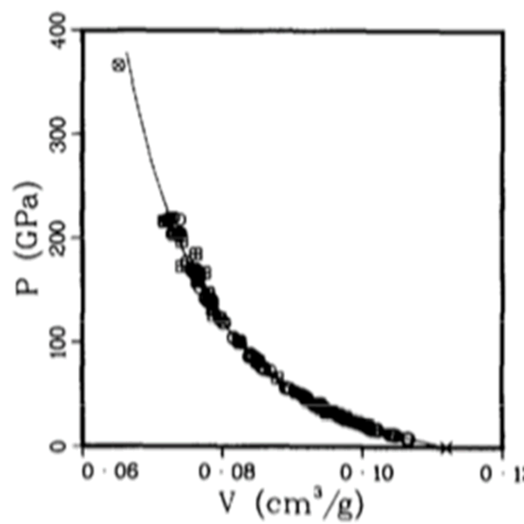




Test Description – Wedge Test

- **When and explosive is subjected to shock just below its detonation pressure, the wave will travel a run-to-detonation distance before being converted to a full detonation wave. Tests are conducted with varied input pressures.**

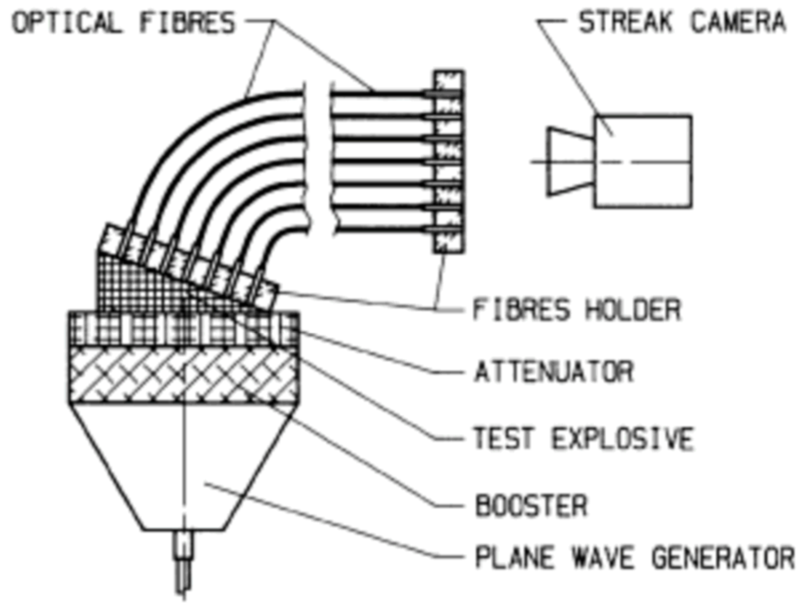


Figure 2.24. Wedge test setup with optical fibres/streak camera recording technique

Sućeska, M., Test Methods for Explosives, Springer, 1995.

Test Description – Wedge Test

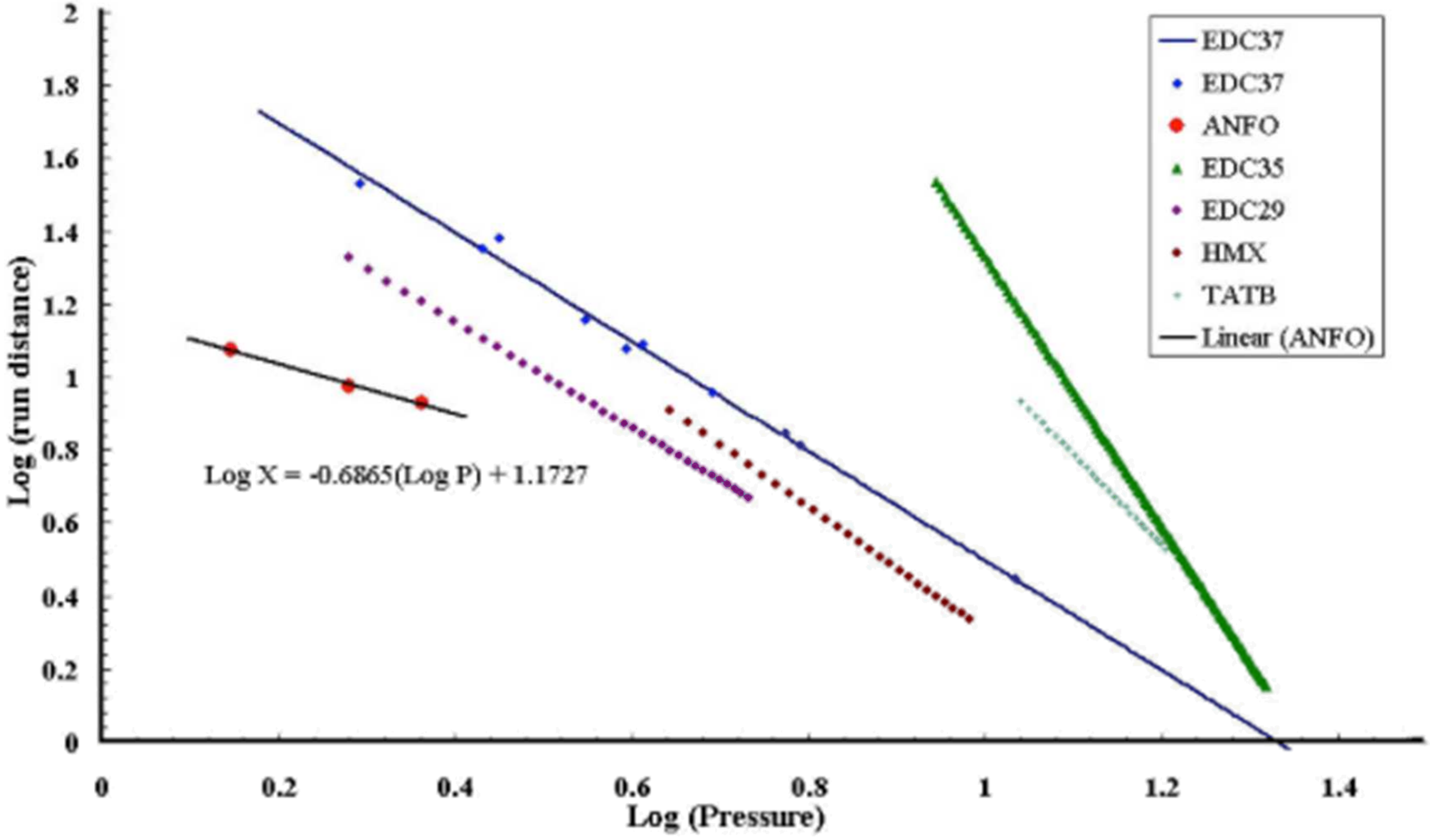
Table 2.10. The possibility of obtaining shock waves of different pressure

Booster (25.4 mm thick)	Attenuator		Shock wave pressure, MPa	
	Material	Thickness, mm	At attenuator entrance	At attenuator exit
TNT	Al 2024	12.7	18.5	13.5
LX-04	Brass	25.4	27.0	10.5
Baratol	Brass	12.7	18.0	6.5
Baratol	Brass	12.7	15.0	5.5
Baratol	Brass	19.1	10.0	3.5
Baratol	Brass	12.7	6.0	1.9

Note: Baratol—mixture of $Ba(NO_3)_2$ and TNT at different mass ratios.
Source: After "Safety and Performance Tests for Qualification of Explosives," NAVORD OD 44811, Naval Weapons Center, China Lake, CA, 1972.

Sućeska, M., Test Methods for Explosives, Springer, 1995.

Test Description – Wedge Test



Burns, M. and Taylor P., "A Study of SDT in an Ammonium Nitrate (NH_4NO_3) Based Granular Explosive", CP955, Shock Compression of Matter, 2007.

Test Description Cont.

- **What agency/organizations paid for the testing:**
  - A majority of the historical shock/particle velocity testing and wedge test data was funded by DOE or DoD.
  - On going testing may be funded by US Gov, other Gov, Universities, etc. They are basic science so show up in many places. New materials continue to be tested as needed and funding becomes available.
- **What is the data being used for:**
  - Data is basic science and used to feed equation of state (EOS) development.
- **Access level and Users of data:**
  - Basic science data is Unclassified Unlimited Release.
  - EOS information is typically UUR, but if the material itself is sensitive increased handling restrictions may apply.
  - EOS data is part of the CTH/Sierra/Zapotec tool package.
  - Modeling results from CTH can be UUR or higher depending on the sensitivity of the scenario modeled.
- **Follow on Tests**:
  - New materials continue to be tested as needed and funding becomes available.
  - To increase our capability to perform high fidelity modeling on explosives not included in the library (e.g. many improvised explosives), testing should be performed to properly characterize them.