SAND2015-3008PE

Exceptional service in the national interest

Sandia National Laboratories

Sandia's Shock Physics Capabilities for National Security Applications

Dr. Gordon Leifeste; Department 1647

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Information for National Security Sponsors

The following information is for the benefit of sponsors of National Security work that is based on and uses Sandia's Shock Physics facilities. The package presents an introduction to the laboratory capabilities and suggests a dialogue that is helpful to plan and execute a successful set of experiments. The capabilities are predominately anchored in Center 1600. The Center provides the stewardship of the STAR Facility, DICE Facility, Z Facility, along with two departments of experimental and theoretical physicists for executing experiments and developing first principal models of matter at extreme pressures and temperatures. Sandia is second to none when it comes to high temperature/high pressure condensed matter studies. The absolute uniqueness of Z with it's capabilities, the STAR hypervelocity launcher, and DICE/ICE all contribute to Sandia being the only National Laboratory and facility in the world capable of conducting research in this regime.

Dr. Gordon Leifeste (gtleife@sandia.gov)

September 2012

Sandia National Laboratories

Dynamic Material Properties are Important to National Security Initiatives

- National Security Initiatives, including Stockpile environment qualification for mechanical effects, relies on accurate mechanical response calculations
- Models require material properties including stress-strain information and yield behavior
- STAR, DICE, and Z have a complete suite of gun and pulsed power platforms that provides for equation of state, code validation, and pressure shear experiments
- Quasi-Isentropic (ICE) Loading techniques can provide data that help evaluate properties that will complement existing techniques, such as rate dependence, damage mechanisms, etc.
- STAR, DICE, and Z have some of the most advanced diagnostics in the world including radiography, photography, and interferometry

Sandia National Laboratories

Directed Stockpile Work (DSW), Life Extension Programs (LEPs), and the Annual Assessment Process

- There is continued interest in probing the current health of materials in existing weapons systems
- Life Extension Programs are seeking to qualify new materials for War Reserve use from new suppliers for use in Nuclear Weapons systems
- An objective is to present the scientific body of evidence that the material is well characterized for weapon system use
- A further objective is to develop science based models, including quantification of uncertainty and predictive performance capability, that can be used by future generations of weapon system engineers

Sandia National Laboratories

Dialogue, Discussions, and Exchange of Ideas: Questions 1600 Will Ask Before Preparing Experiments

- Describe the technical objectives of the National Security program in enough detail to help stimulate thinking for the "Design of Experiments" section
- Do you have "quasi-static" data from vendors
- Do you have material samples and subassemblies available for pre-shot measurements
- Do you have electronic mechanical models (ex. SolidWorks)
- What experimental measurements and post-shot analysis are appropriate
- "Design of Experiment" discussions
- What level (expectations) of documentation is appropriate
  - Slides
  - SAND report
  - Refereed publication
- What level (expectations) of first principal physics model development is appropriate
- What level of onsite, sponsor participation is desired and appropriate
- Will there be sponsor supplied diagnostics
- Cost estimate
- Schedule request

Sandia National Laboratories

Discussions Will Determine What Pre-shot Measurements May be Required

- Quasi-static mechanical properties
  - Compressive strength : Maximum stress a material can withstand before compressive failure (MPa)
  - Density : Mass per unit volume (kg/m^3)
  - Ductility : Ability of a material to deform under tensile load (% elongation)
  - Fatigue limit : Maximum stress a material can withstand under repeated loading (MPa)
  - Fracture toughness : Energy absorbed by unit area before fracture of material (J/m^2)
  - Hardness : Ability to withstand surface indentation (e.g. Brinell hardness number)
  - Plasticity: Ability of a material to undergo irreversible deformations
  - Poisson's ratio : Ratio of lateral strain to axial strain (no units)
- Quasi-static mechanical properties
  - Shear modulus : Ratio of shear stress to shear strain (MPa)
  - Shear strain : Change in the angle between two perpendicular lines in a plane
  - Shear strength : Maximum shear stress a material can withstand
  - Bulk modulus : Modulus per unit volume (MPa/ m^3)
  - Tensile strength : Maximum tensile stress a material can withstand before failure (MPa)
  - Yield strength : The stress at which a material starts to yield (MPa)
  - Young's modulus : Ratio of linear stress to linear strain (MPa)
  - Coefficient of friction (also depends on surface finish)
  - Coefficient of restitution

Sandia National Laboratories

Discussions Will Determine What Pre-shot Measurements May be Required

- Thermal properties
  - Coefficient of thermal expansion
  - Curie point
  - Melting point
  - Phase diagram
  - Specific heat
  - Thermal expansion
- Material properties
  - Composition
  - Microstructure
  - Grain size
  - Grain orientation
  - Porosity

Sandia National Laboratories

Measurements and Post-shot Analysis: What Will be Useful for Your Project?

- Recovery of subassemblies and samples
- Photography
- Radiography
- Interferometry
- Hugoniot Elastic Limit (HEL): The maximum stress a material can withstand under uniaxial shock compression without internal rearrangement
- Hugoniot Equation of State (HEOS)
- Dynamic high pressure strength
- First principal model

Sandia National Laboratories

Shock Physics Program at Sandia

- Shock physics experiments are designed to investigate properties of gases, fluids, and solids when exposed to shock waves
- The Nation's Stockpile Stewardship Program as well as other National Security Programs demands that experimental results be detailed in pertinent models to predict/model those results
- Sandia National Laboratories is one of a few institutions in the world with a major high pressure/high temperature condensed matter physics (shock physics) research program
- Sandia has an institutional triad (STAR, DICE, Z) that can cover the full range (few kbars to Mbar) of material property study from
  - gas/propellant guns
  - ballistic gun (validation experiments)
  - ramp-loading pulsars

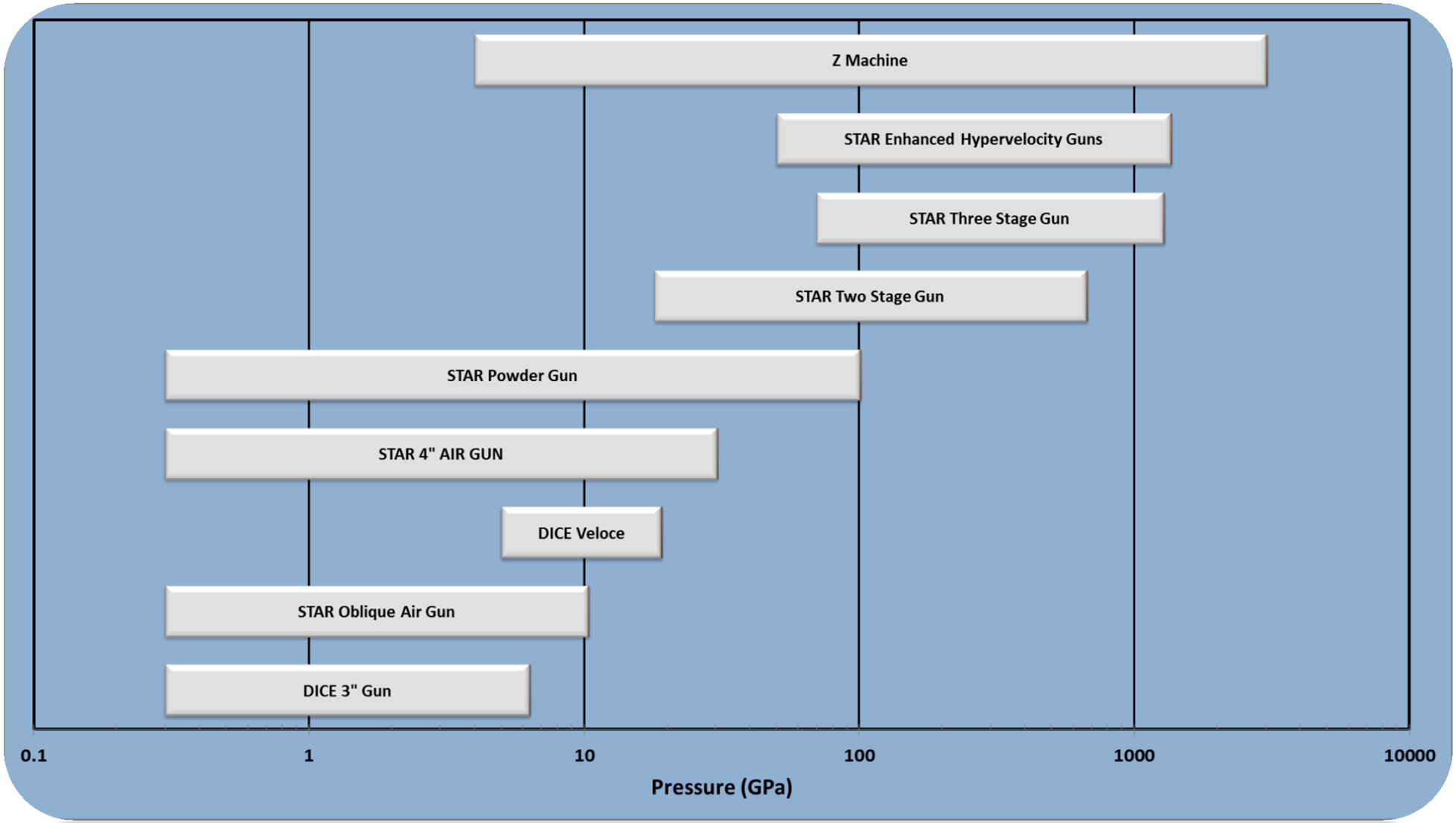
Sandia National Laboratories

Shock Physics Platforms at Sandia

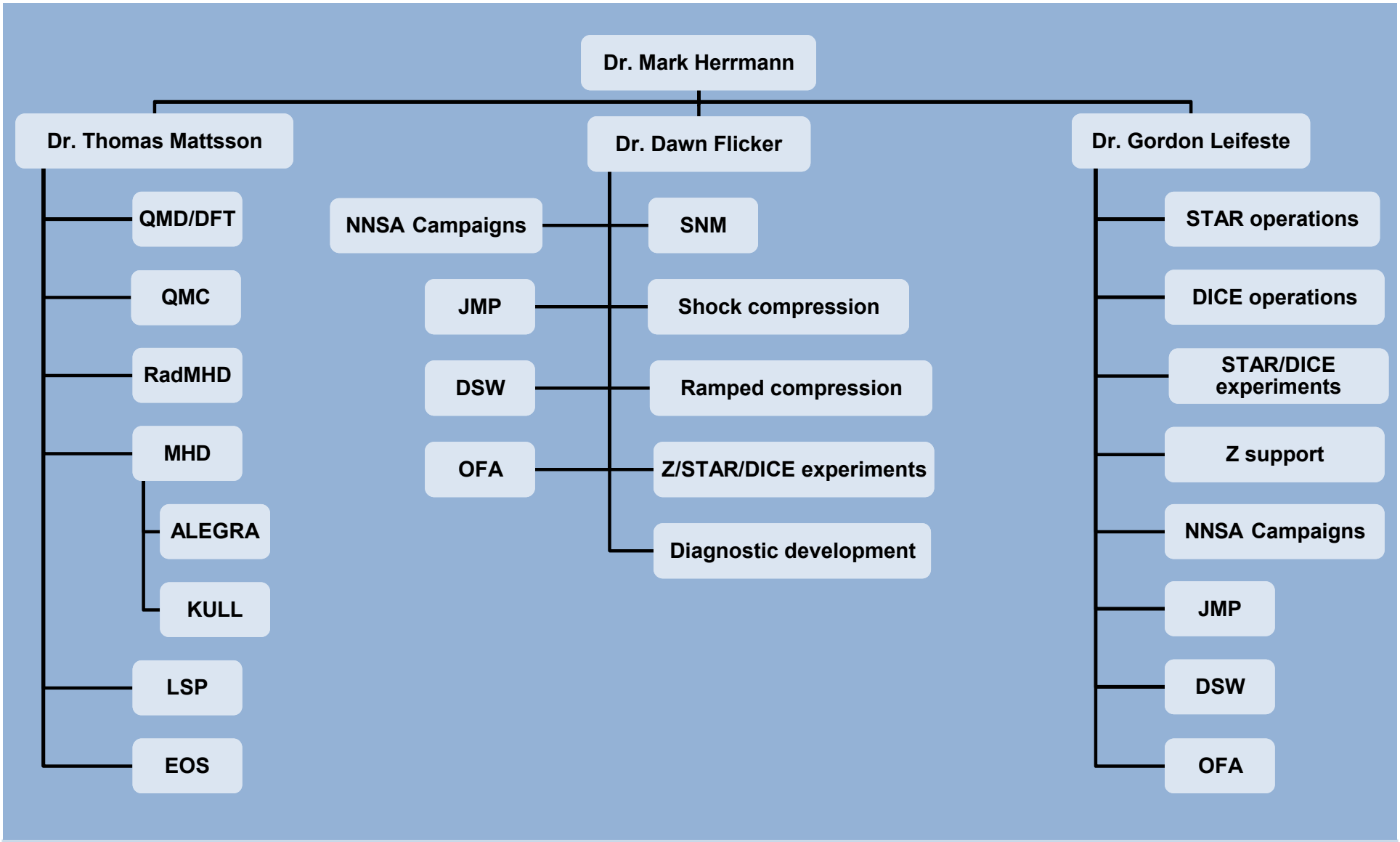
- Center 1600 “owns” the following facilities, provides stewardship of the assets on behalf of the Government, and executes Dynamic Material Property experiments at the STAR Facility, the DICE Facility, and the Z Facility for the NNSA Science Campaign and other National Security customers
- Shock Thermodynamic Applied Research (STAR) facility
  - The STAR facility is a dynamic experimental test facility that has been operating since the mid-60’s
  - The facility houses a collection of five laboratory test launchers (guns)
  - POC: Bill Reinhart; 505-284-3185; wdreinh@sandia.gov
- Dynamic Integrated Compression Experimental (DICE) facility
  - The DICE facility is a dynamic experimental test facility that has been operating since 2010
  - The facility houses a laboratory test launcher (gun) and a small pulse power machine (Veloce)
  - POC: Randy Hickman; 505-284-3813; rjhickm@sandia.gov
- Z machine
  - The Z Facility is a pulsed power based test facility that has been operating since 2005
  - The Z machine is located in Tech Area 4/building 983
  - Over 50% of the shots on Z are in support of Dynamic Material Property experiments within the NNSA Science Campaign
  - POC (Shock Physics studies): Dawn Flicker; 505-845-7398; dgflick@sandia.gov

Sandia National Laboratories

Sandia's World Class Experimental Facilities Provide a Wide Range of Regimes that can be Exploited for DM Experiments



High Pressure/High Temperature Condensed Matter Physics Research at Sandia



Sandia National Laboratories

Center 1600 Perspective

- The combination of Departments 1647, 1646, and 1641 along with the Z machine constitute a high pressure/high temperature condensed matter physics (shock physics) program second to none in the world
- Most National Security shock physics work involves large impactors and targets. Gun facilities are the platforms of choice for these experiments and makeup the bulk of the National Security shock physics work
- The three stage gun configuration at STAR is unique in the world for launching flyer plates up to 12 km/sec for Equation of State (EOS) studies
- The oblique gun at STAR is a unique National capability
- The Z Facility has a formal proposal process to allocate shots and is not covered in this package

Sandia National Laboratories

General Comments for DOE Facilities

- The capabilities within the DOE are often supported by small projects across multiple U.S. Government Agencies with no single dominant long-term program serving as the dominant national steward for these capabilities
- In spite of this fact, many existing U.S. security systems incorporate approaches, technologies, or procedures first conceived of or demonstrated in the DOE National Laboratories
- The DOE labs offer an ability to easily integrate expertise across diverse scientific and engineering disciplines and to bridge the gap between scientific discovery and the engineering required to field integrated systems
- They also function effectively as part of the U.S. National Security enterprise with their ability to support and conduct classified work

Sandia National Laboratories

General Comments for DOE Facilities

- Many of the assets at the DOE labs are at some risk of atrophy
- The Labs have difficulty sustaining and nurturing the expertise and capabilities with support provided by a multiagency sponsor base that preferentially funds small, short term projects
- Capabilities at risk from a combination of factors including
  - A retiring workforce;
  - declining budgets;
  - small projects of short duration; and
  - pressure from industry and academia that attracts much of the young emerging talent

Sandia National Laboratories

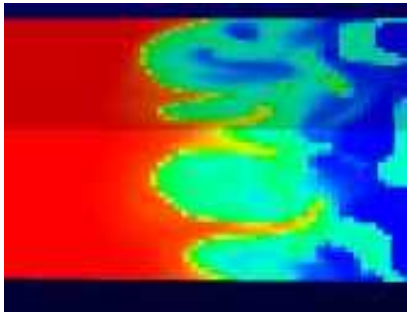
Sandia's Gun Facilities

- Sandia's gun facilities can test nearly any type of material, solid or liquid, from explosives (PBX, Comp-B, reactive), chem/bio simulants, depleted uranium, ceramics, powders, etc.
- The facilities staff combine decades of experience in experimentation, data analysis (theoretical to practical), and modeling
- The technical staff collaborates with other Sandia theorists and computational experts to implement numerous codes including CTH which is a multi-material, large deformation, strong shock wave, solid mechanics code developed at Sandia National Laboratories

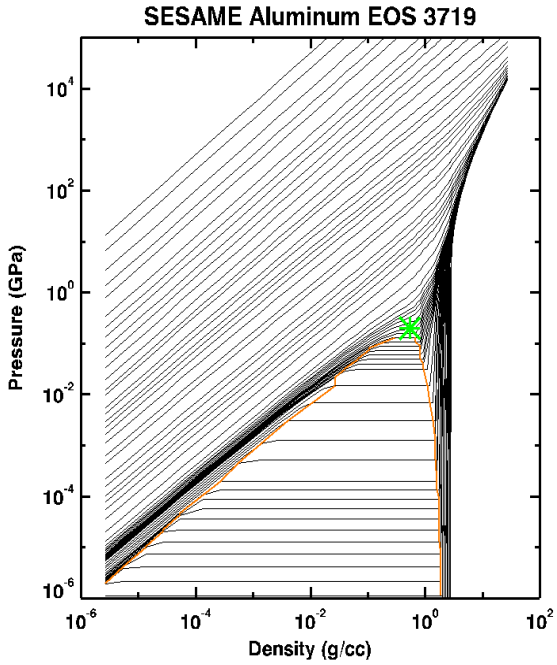
Sandia National Laboratories

High-fidelity Tabular EOS are Required for Hydrodynamic Simulations to be of High Quality/Predictive

- The equation of state (EOS) $P(\rho,T),E(\rho,T)$ governs the hydrodynamic- and thermal evolution of a material
- Primitive EOS are analytical equations – EOSs used in advanced simulation codes are tabulated over a wide-range of (ρ,T)
- Deficiencies in EOS can never be augmented with mesh, solvers or massively parallel computing
- 1641 & 1443 have worked together on developing tabular EOS for a broad range of materials, for example Al, W, Au, Cu, quartz, Xe



Hydro simulations of a solid with shock melting and vaporization

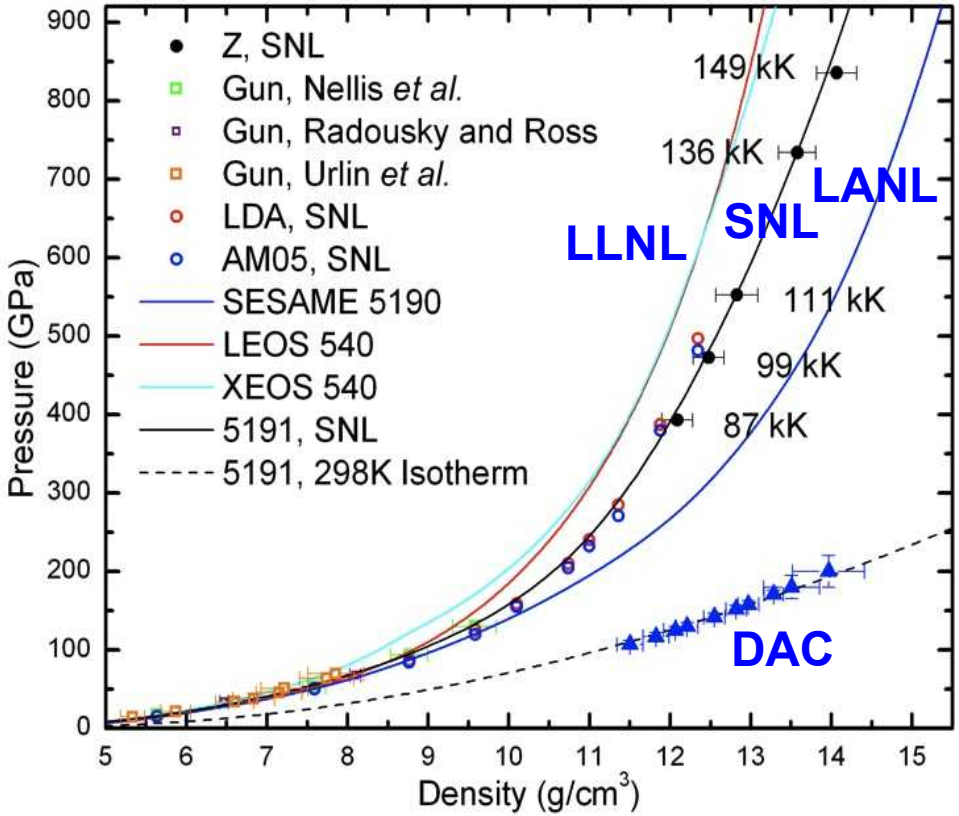


Wide-range EOS for aluminum SESAME 3719

Sandia National Laboratories

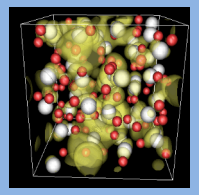
Developing a Tabular EOS Using First-principles Simulations, Thermodynamic Data, and Shock Experiments

- Density Functional Theory (DFT)
  - Based on quantum mechanics – no empirical parameters/ fits
  - Quantum Molecular Dynamics (QMD)
  - Calculate energy, pressure, structure, diffusion, electrical conductivity, and more
  - Large-scale simulations on supercomputers
- Develop a tabular EOS by using
  - Data from shock experiments using guns and, if needed, multi-Mbar data from Z
  - Results from DFT/QMD
  - Thermo-physical data like specific heat, thermal expansion
  - Static data from diamond anvil cells



1641/1443 developed a new tabular EOS for Xe with superior performance compared to previous EOSs from LANL and LLNL

Walter Kohn was awarded the 1998 Nobel prize in chemistry for DFT



Simulate motion of hundreds of atoms to calculate thermodynamic properties

Sandia National Laboratories

The STAR Facility

- The STAR facility stands for ***Shock Thermodynamic Applied Research***
- Facilities such as STAR are specifically designed, staffed, and used by professionals in the technical disciplines of High Temperature/High Pressure Condensed Matter Physics (Shock Physics, Dynamic Material Properties)
- The STAR facility (Bldg. 9956; Coyote Test Field) is an experimental test facility that began in the mid-60's as two guns in one gun bay
- Improvements were made during the mid-80's. The improvements consisted mainly of new gun bays and new launchers

Sandia National Laboratories

The STAR Facility

- The facility of about 16,000 square feet currently houses a collection of five laboratory test launchers (guns) in four gun bays for Dynamic Material Property studies and a small machine shop
- The guns are either propellant driven or compressed gas driven systems
- STAR also has a multiple array of small caliber arms
  - Conventional velocities are used to study
    - Construct penetration
    - Body armor resistance
    - Code validation

Sandia National Laboratories

The STAR Facility

- A typical STAR shot consists of a projectile with an impactor on the front surface being launched (by propellant or compressed gas) down the gun barrel
- The impactor hits a target sample, usually a solid or granular material, mounted in a target holder and the debris from the high speed projectile/impactor/target collision is contained in a catcher tank
- Diagnostics characterize the impact and the material response
- The catcher tanks are sized to hold material to slow down and then stop the debris
- The material ranges from “parachute fabric” to honeycomb material to thick steel plates, depending on the gun

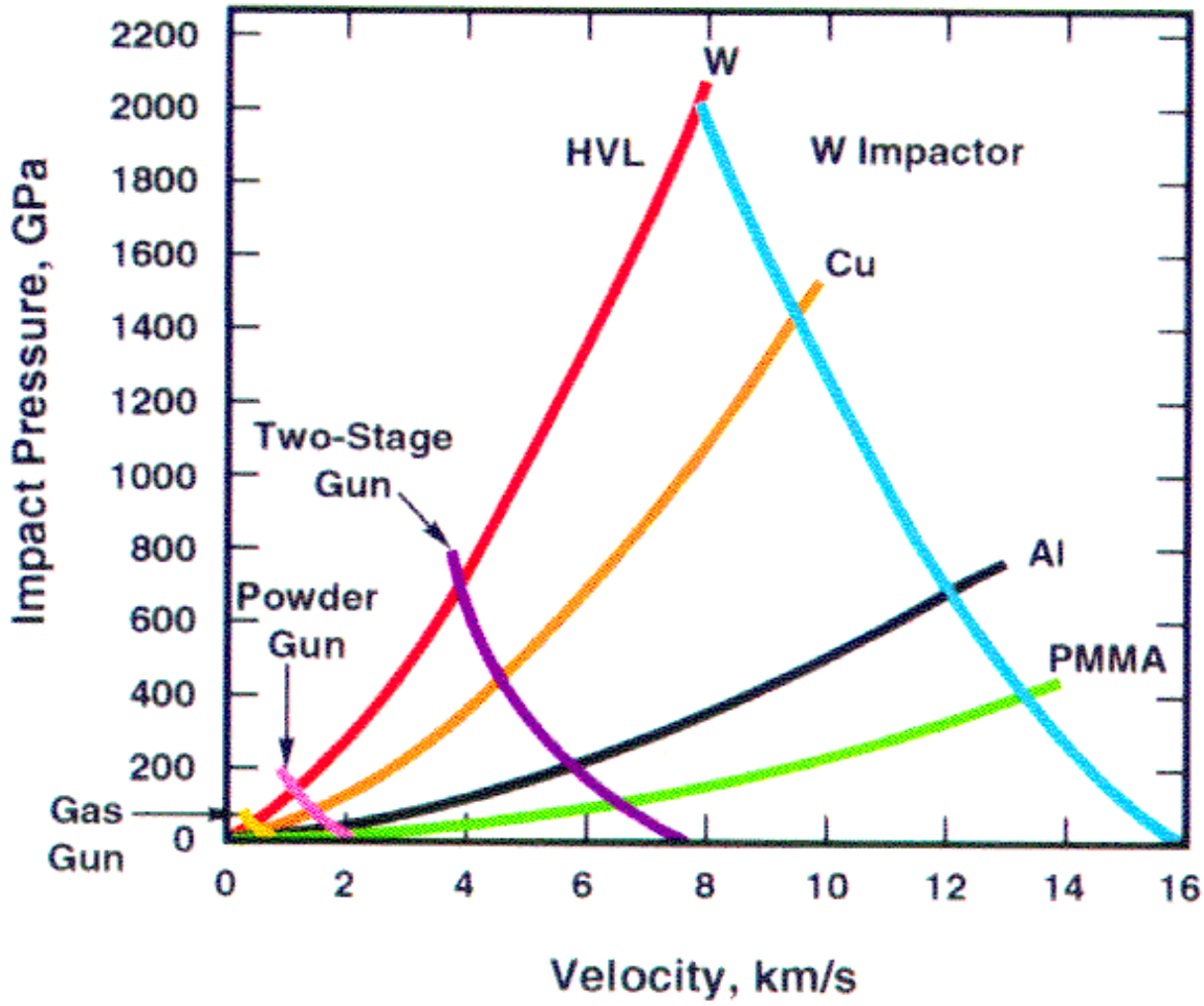
Sandia National Laboratories

STAR Sponsors

- Over the past decade the facility is generally fully subscribed
- The challenge is always at the start of the physical year to have sponsors commit to work at the facility and then create a schedule for the year
- The facility has performed work for a broad customer base mainly on behalf of:
  - NNSA
    - DSW;
    - Science Campaign; and
    - Other Sponsors
  - Other Federal Agencies (OFA)
    - DoD;
    - DHS; and
    - NASA

Sandia National Laboratories

Performance Range of the STAR Facility

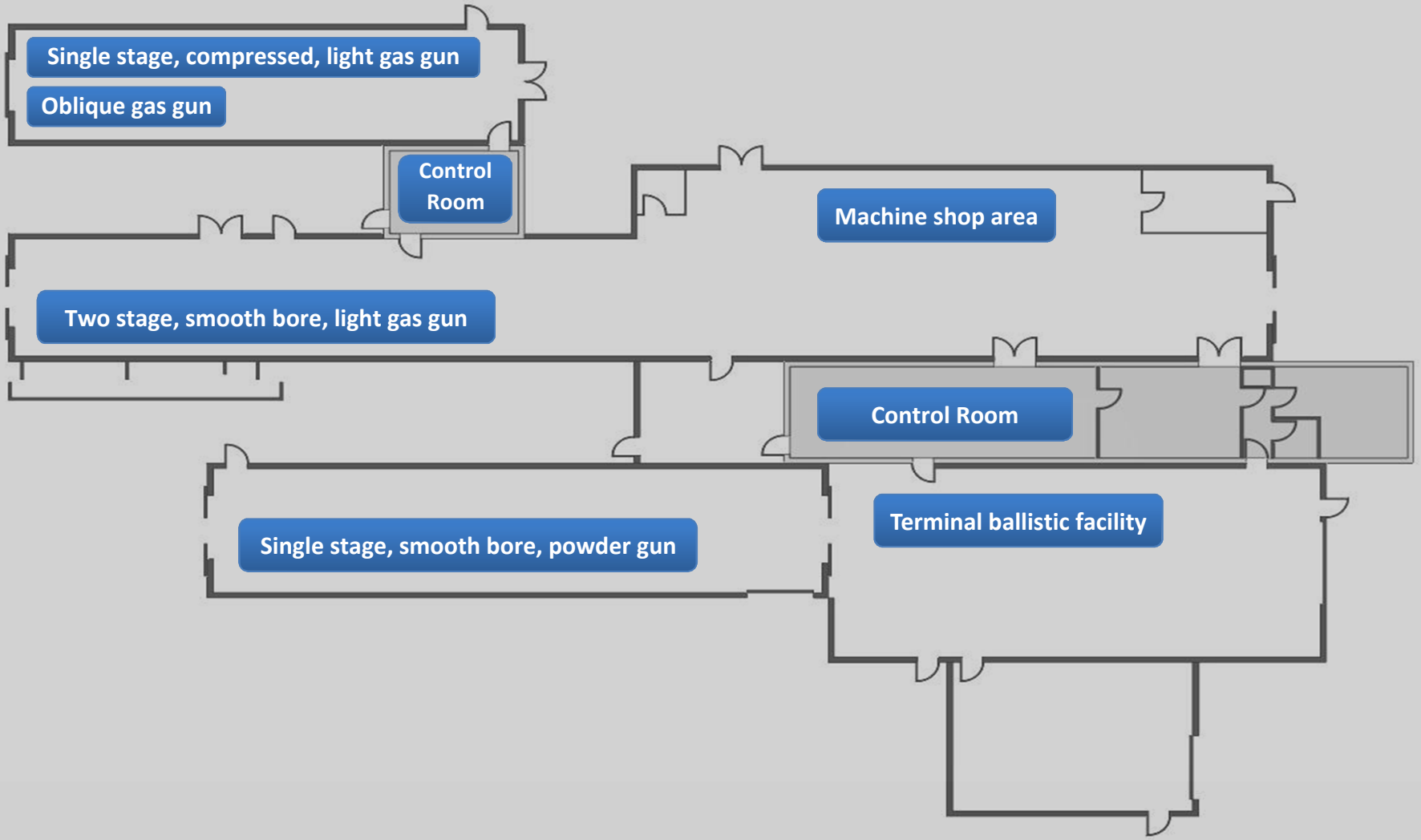


Sandia National Laboratories

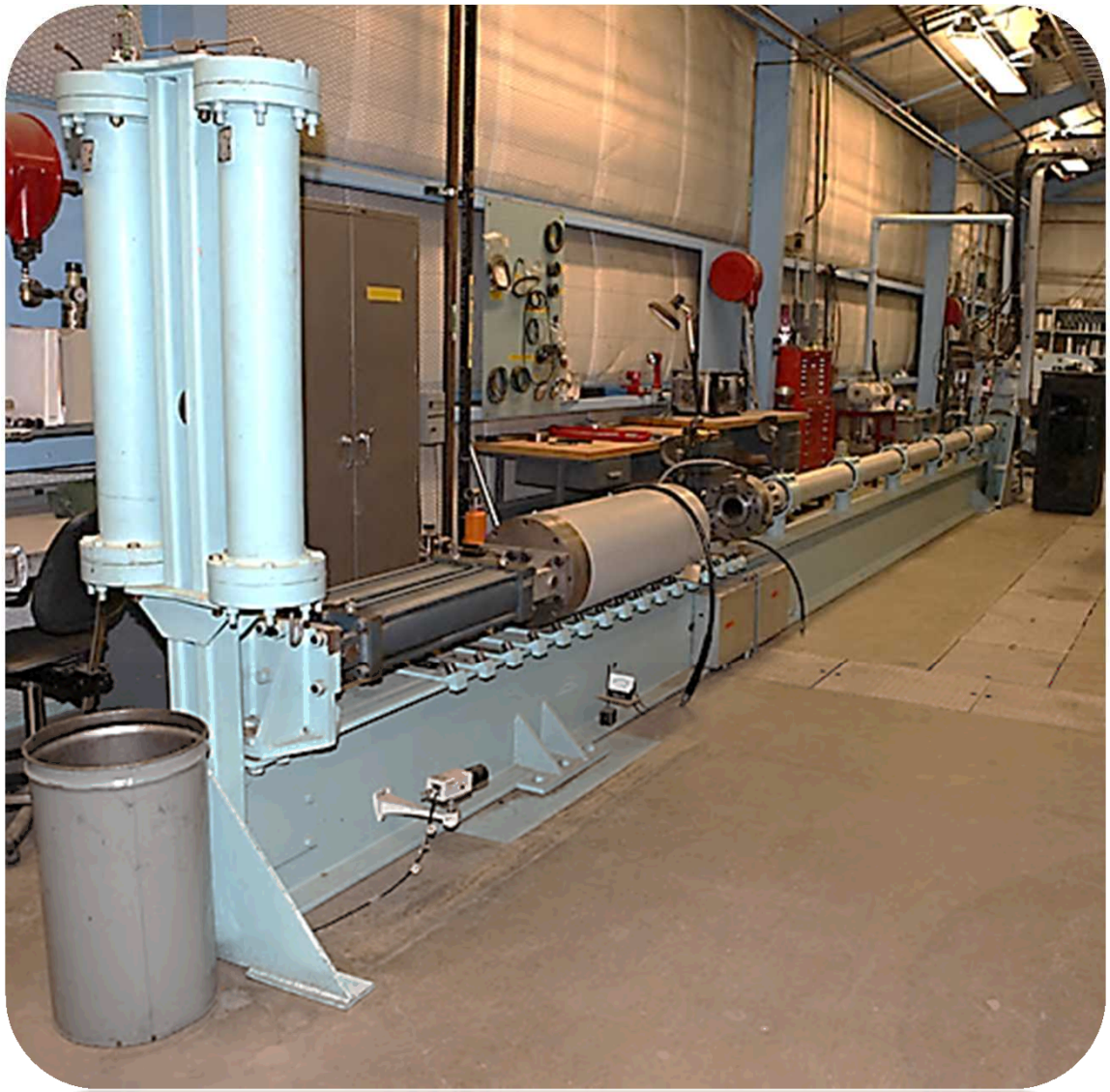
The STAR Facility: Bldg. 9956/Coyote Test Field

Sandia National Laboratories

STAR Layout


Single stage, compressed, light gas gun
Oblique gas gun
Control Room
Machine shop area
Two stage, smooth bore, light gas gun
Control Room
Terminal ballistic facility
Single stage, smooth bore, powder gun

Single Stage, Smooth Bore, Compressed Light Gas Gun



- Compressed gas driven
- 100 mm bore diameter
- 900-9000 gm projectile mass
- 0.01 – 1000 m/s projectile velocity
- 30 GPa (300 kbar) impact pressure

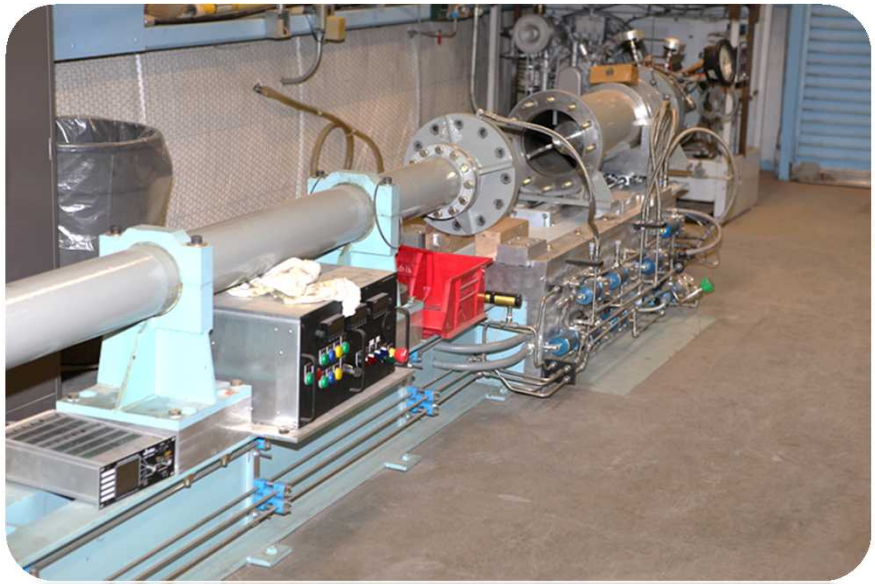
Sandia National Laboratories

Single Stage, Smooth Bore, Powder Gun

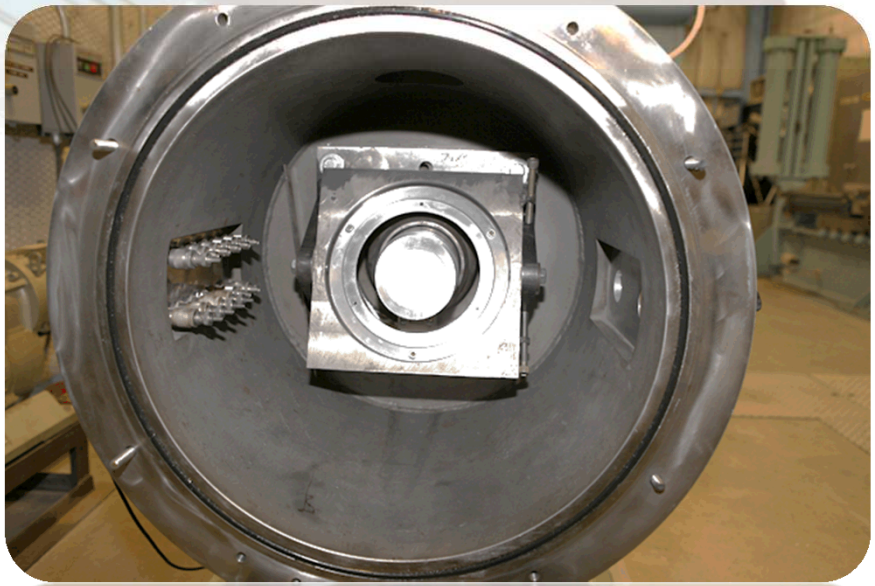
- Propellant driven (9000 grams/19.8 pounds maximum fill)
- 89 mm bore diameter
- 900-9000 gm projectile mass
- 400 – 2200 m/s projectile velocity
- 100 GPa (1Mbar) impact pressure

Sandia National Laboratories

Single Stage, Keyed-bore Compressed Light Gas Gun (aka Oblique Gun)



- Compressed gas driven
- 100 mm bore diameter
- 500-5000 gm projectile mass
- 50-350 m/s projectile velocity
- 10 GPa (100 kbar) impact pressure



Sandia National Laboratories

Two Stage, Smooth Bore, Light Gas Gun

- Propellant driven (9000 grams/19.8 pounds maximum fill)
- 20, 30, 67 mm bore diameter
- 15-60 gm projectile mass
- 800 – 7500 m/s projectile velocity
- 650 GPa (6.5 Mbar) impact pressure
- Three stage/HVL/EHVL=Two stage gun + fixtures
  - The three stage gun configuration is unique in the world for launching flyer plates for Equation of State (EOS) studies up to 12km/sec

Sandia National Laboratories

Terminal Ballistic Facility

- Propellant driven (200 gm/0.44 pounds maximum fill)
- Propellant driven
- Two stage, smooth bore, light gas gun
- 6-30 mm bore diameter
- 1-60 gm projectile mass
- 800-7500 m/sec projectile velocity
- 650 GPa (6.5 Mbar) impact pressure

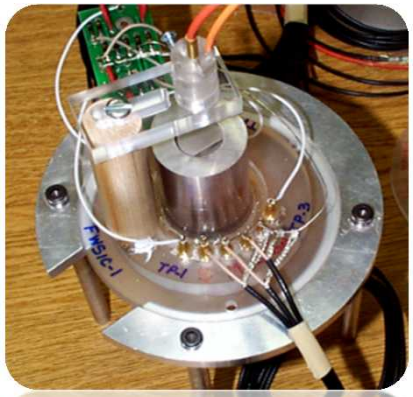
Sandia National Laboratories

Ballistic Studies at the STAR Facility

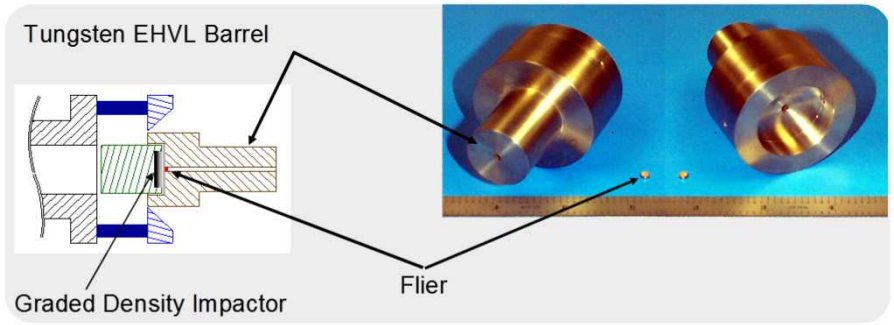
- Utilize two-stage light gas gun and range for investigations into material fragmentation, spacecraft studies, and code validations on scaled targets
- Validation experiments can be performed with virtually any geometric shape impactor
- Impacts up to 19 km/s for space applications: micrometeoroid, space junk, etc..
- Sandia is the only institution that incorporates low-pressure target chambers for hypervelocity impacts exceeding 10 km/s
- Radiography, photography, velocimetry, interferometry

Sandia National Laboratories

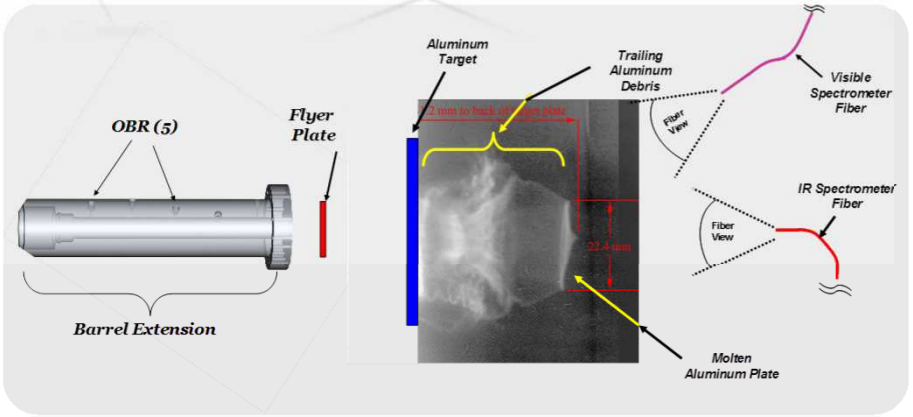
Capabilities, Tools, Diagnostics, and Advancements at STAR

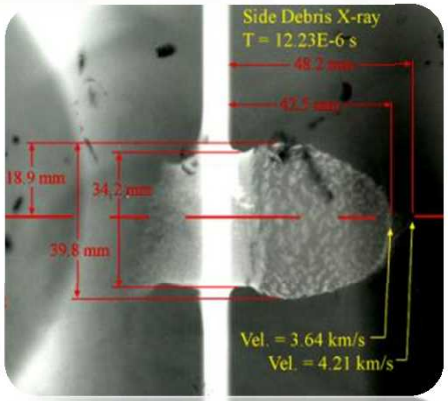


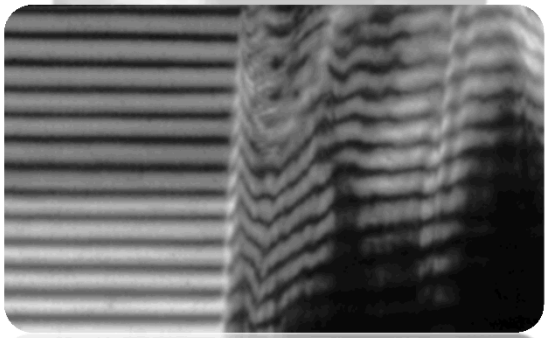
Electrical Diagnostics



High speed Photography



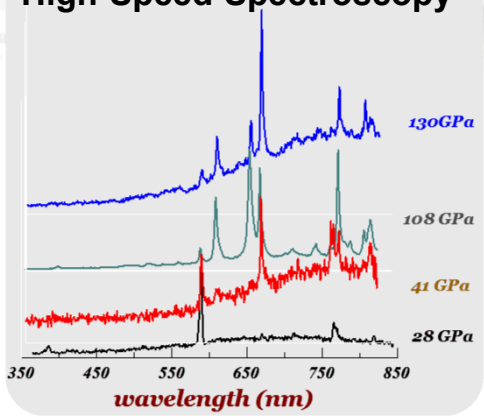


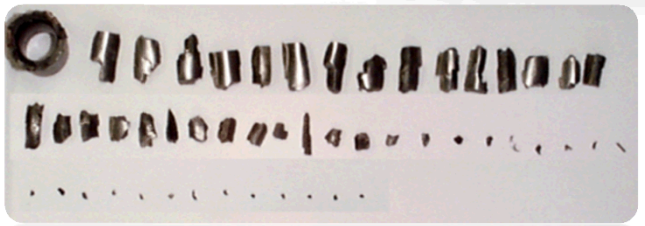


Line VISAR Interferometry

Radiography

High-Speed Spectroscopy

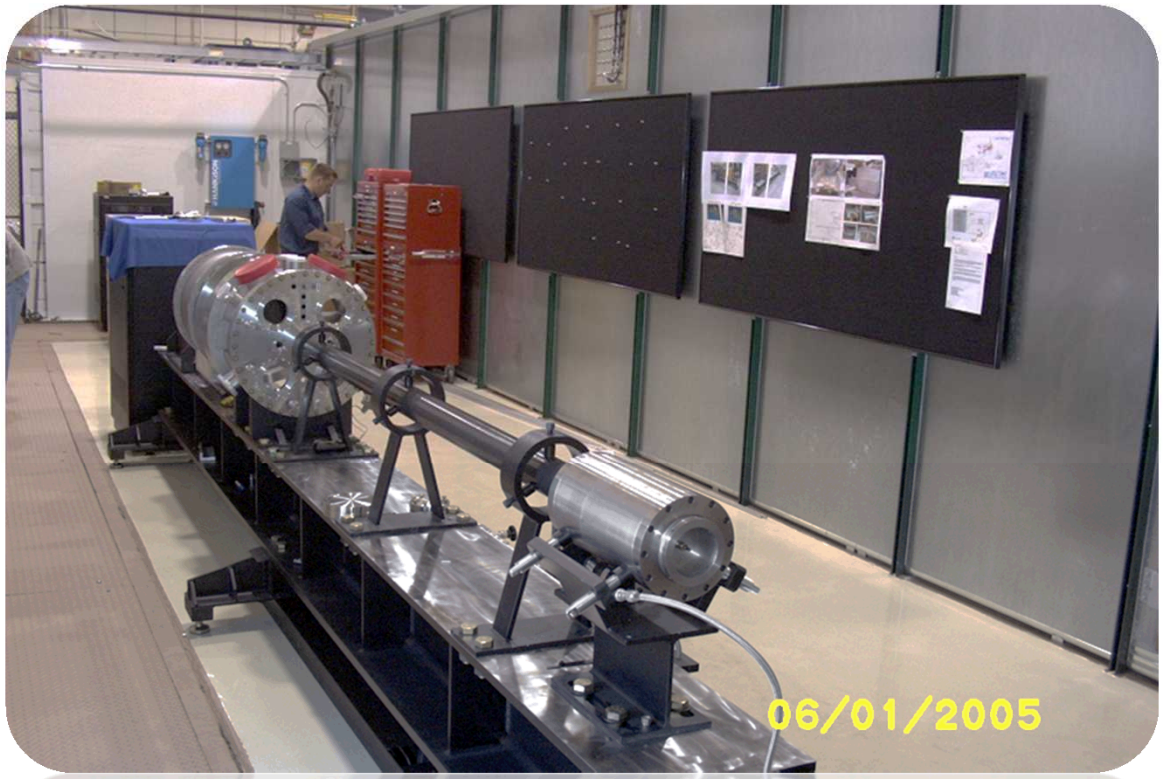




Fragmentation

Sandia National Laboratories

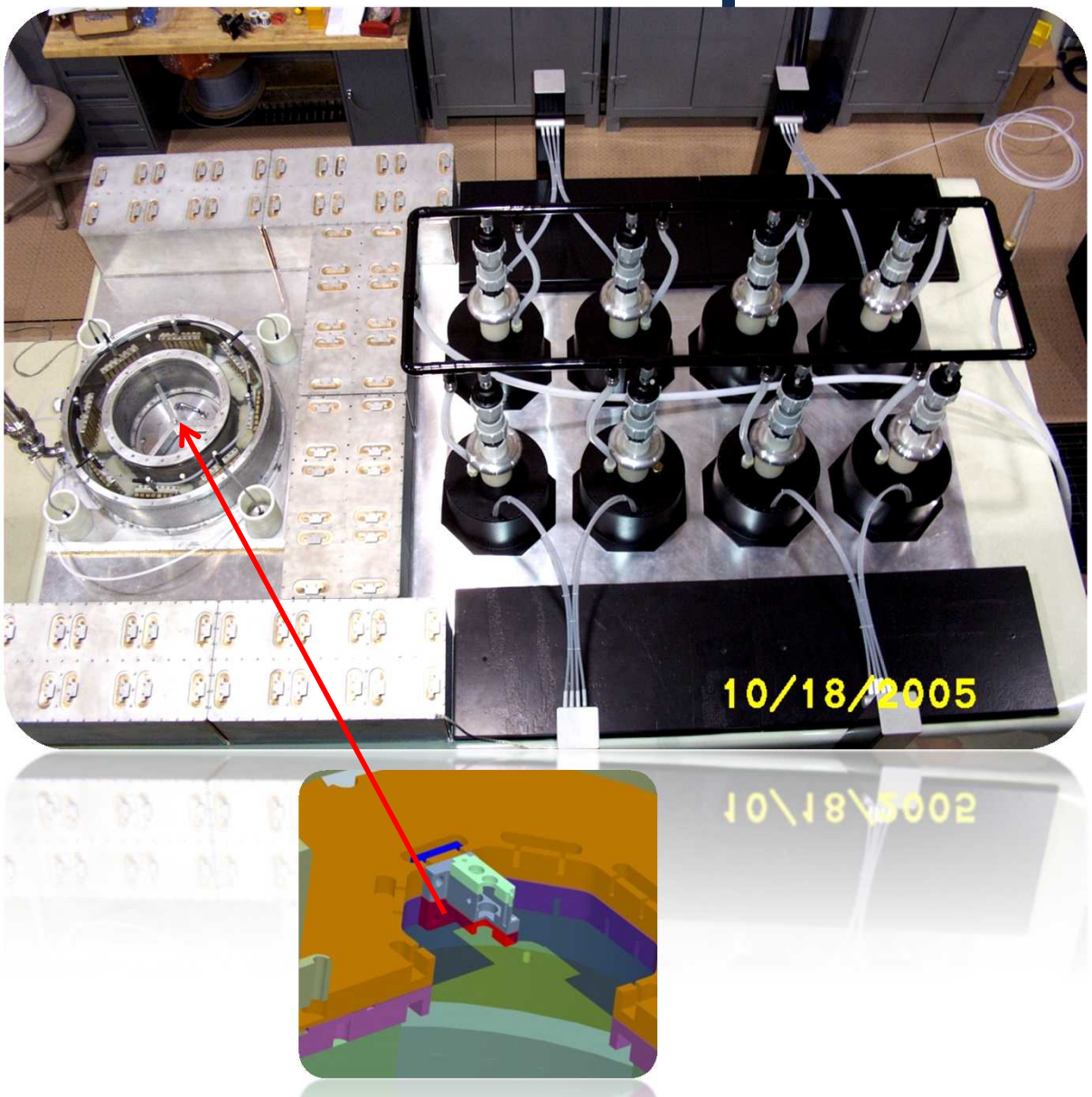
DICE Gun

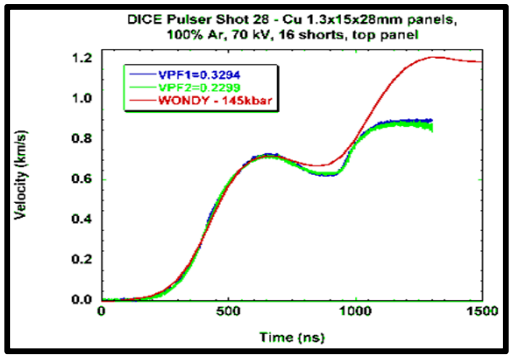


- Compressed gas driven
- 76mm bore diameter
- 240-540 gm projectile mass
- 80-450 meters/second velocity
- 0.3-6 GPA (60kbar)
- VISAR, Line ORVIS, X-Ray diffraction
- Soft sample capture

Sandia National Laboratories

DICE VELOCE: Isentropic (Ramp) Compression

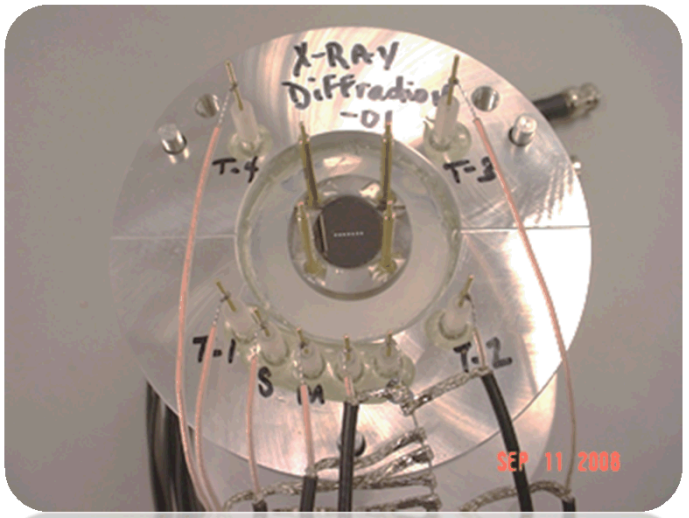




- 10mm-30mm Panels
- 8-26mm sample diameter
- 420-540ns rise times
- 5-14GPA (140kbar)
- VISAR, Line ORVIS
- Sample Pre-Heating, Pre-Cooling
- Soft sample capture

Sandia National Laboratories

DICE Target Fabrication Laboratory



- Class 1000 clean room
- High Precision weight/mass measurements
- Nikon video precision measurement systems

Sandia National Laboratories