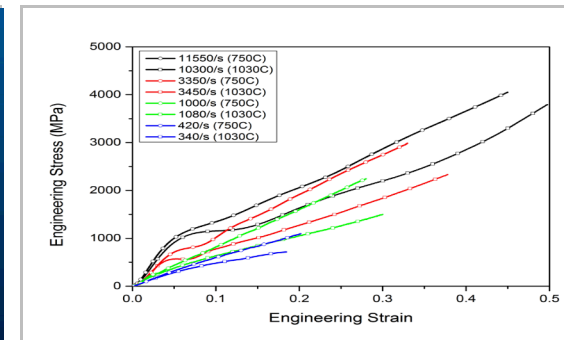
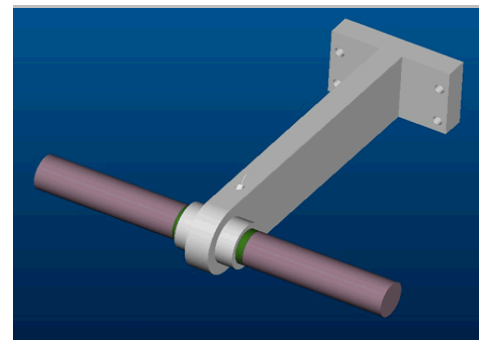
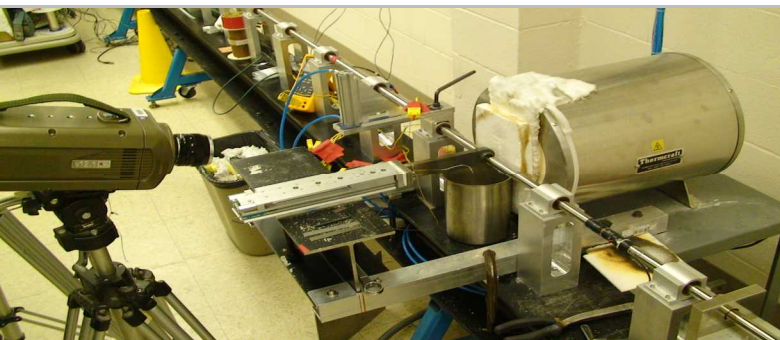


*Exceptional service in the national interest*



Sandia  
National  
Laboratories



# High-Temperature Impact Plasticity Characterization of Iridium

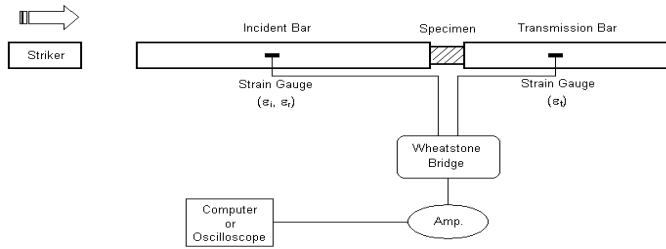
**Bo Song**

*(1558: Experimental Environment Simulation Department)*

# Outline

- **Background**
- **Kolsky bar techniques for dynamic characterization of materials**
  - Challenges in dynamic high-temperature diagnosis (current techniques)
  - Additional challenges in dynamic high-temperature diagnosis on thin Iridium specimens
  - Modifications
- **Dynamic high-temperature characterization of iridium**
  - Experimental procedure
  - Diagnostic uncertainties
- **Experimental Results**
- **Summary**
- **Acknowledgments**

# Kolsky Bar (Split Hopkinson Bar) Techniques



$$\dot{\epsilon} = \frac{u_1 - u_2}{l_0} = \frac{C_b}{l_0} (\epsilon_i - \epsilon_r - \epsilon_t) \Rightarrow \epsilon = \int_0^t \dot{\epsilon}(\tau) d\tau$$

$$\sigma = \frac{F_1 + F_2}{2A_0} = \frac{E_b A_b}{2A_0} (\epsilon_i + \epsilon_r + \epsilon_t) \Rightarrow \sigma \sim \epsilon$$

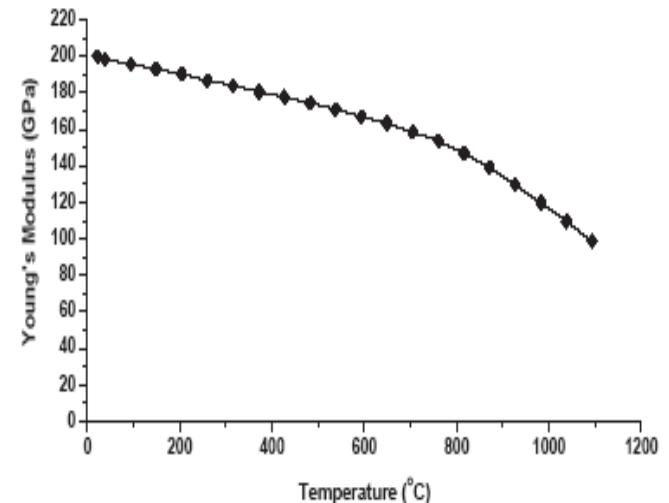
## ■ Kolsky bar for high temperature compression test

### ■ Heat specimen and bar ends

- Hot specimen
- Thermal gradient in the bars

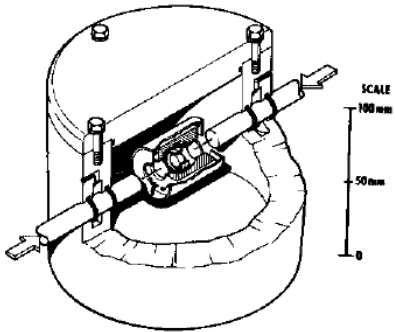
### ■ Heat specimen individually

- Hot specimen
- Cold bars

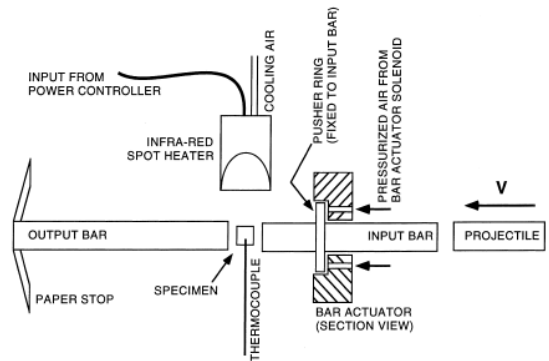


# Current High-Temperature Kolsky Compression Bar Techniques

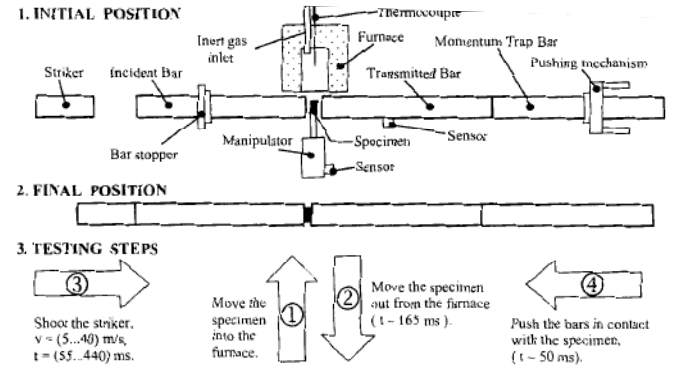
- Hot Specimen/Cold Bars
  - Heat transfer
    - Specimen temperature drops
    - **Bar temperature increases – thermal gradient in the bars**
  - Cold Contact Time (CCT)
    - is the time during which the “hot” specimen stays in contact with the “cold” pressure bars until being dynamically loaded
    - should be as short as possible
      - ~ milliseconds



(Follansbee et al.)  
LANL



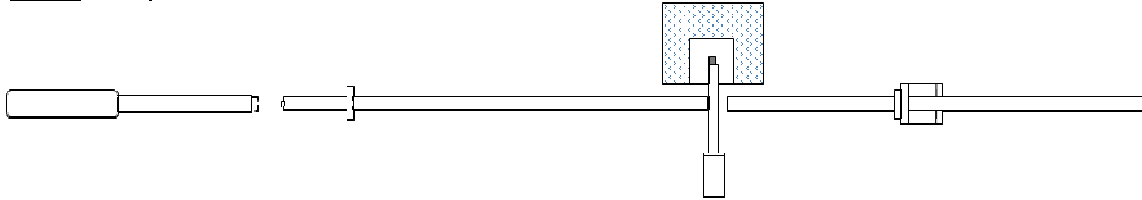
(Ramesh, et al.)  
JHU



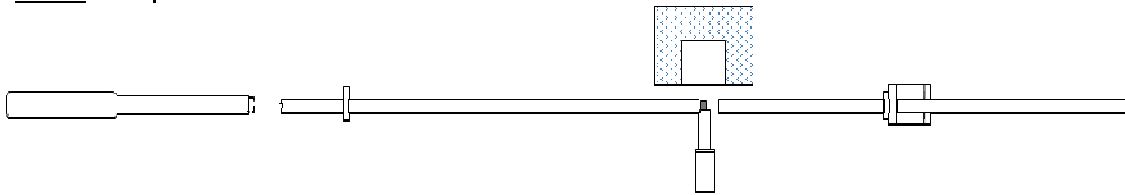
(Kuokkala et al.)  
FINLAND

# Kuokkala's High-Temperature Kolsky Compression Bar

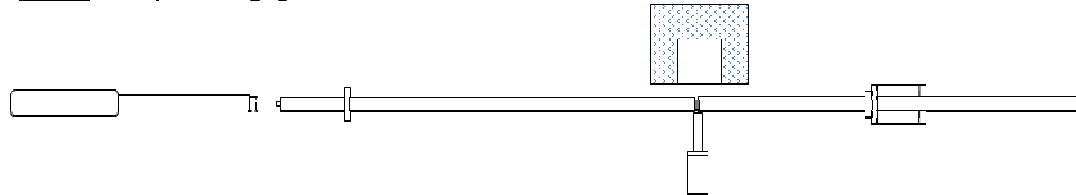
**STEP 1:** Sample moved to furnace



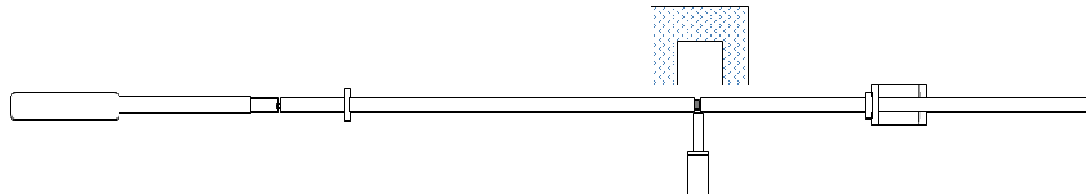
**STEP 2:** Sample removed from furnace



**STEP 3:** Sample is engaged

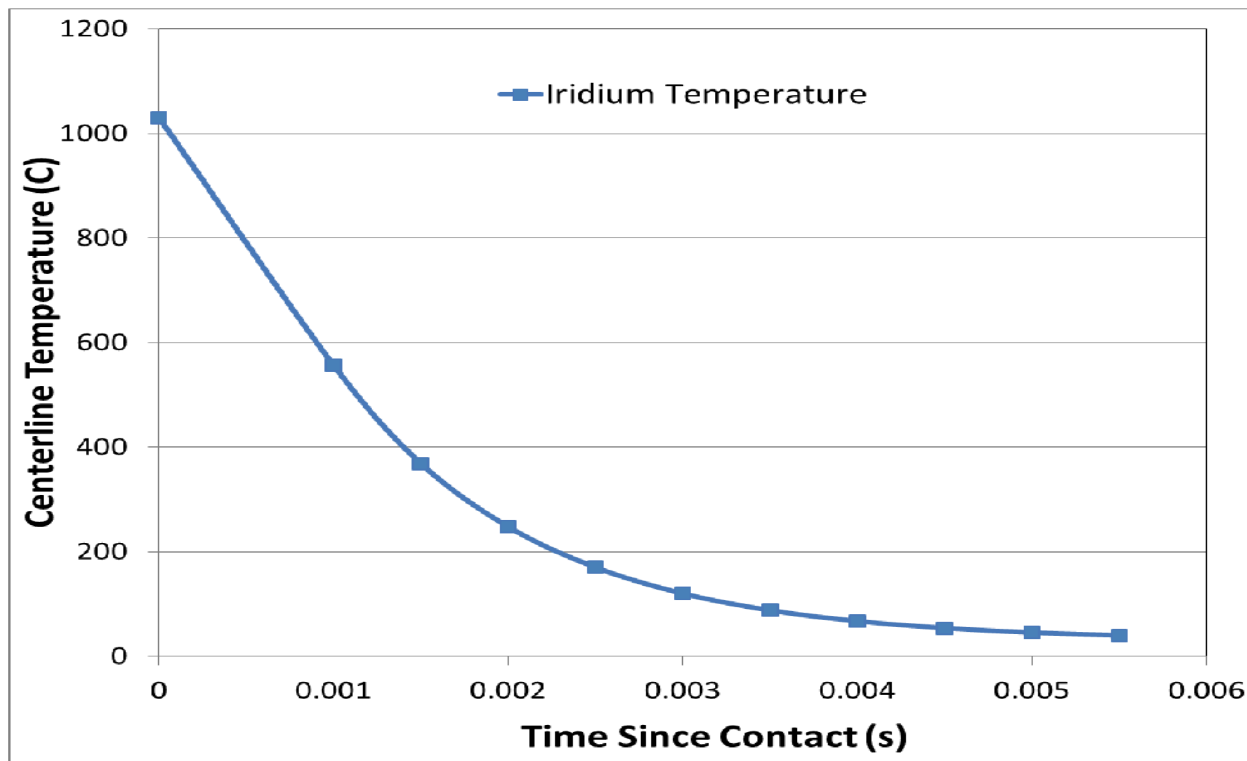


**STEP 4:** Striker is fired



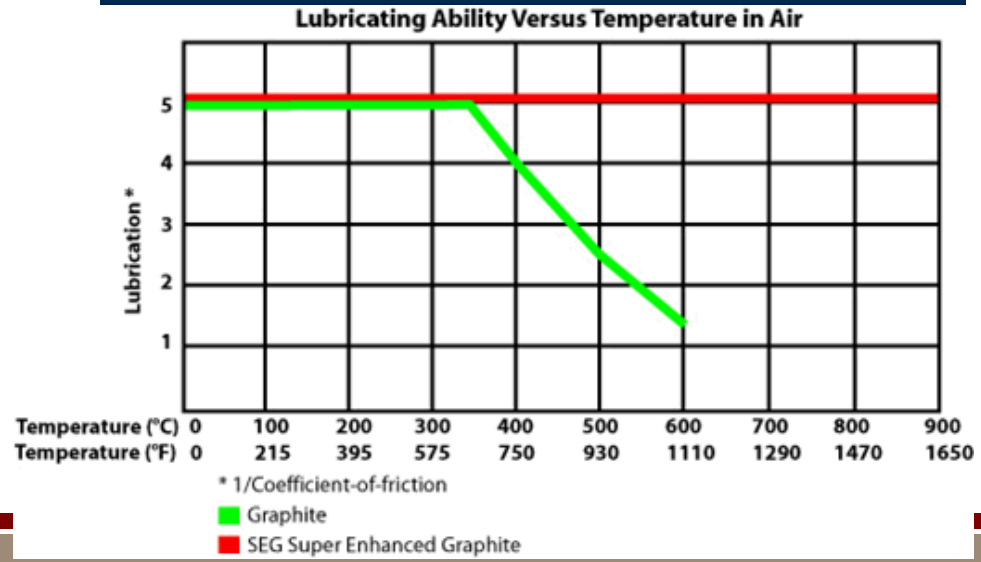
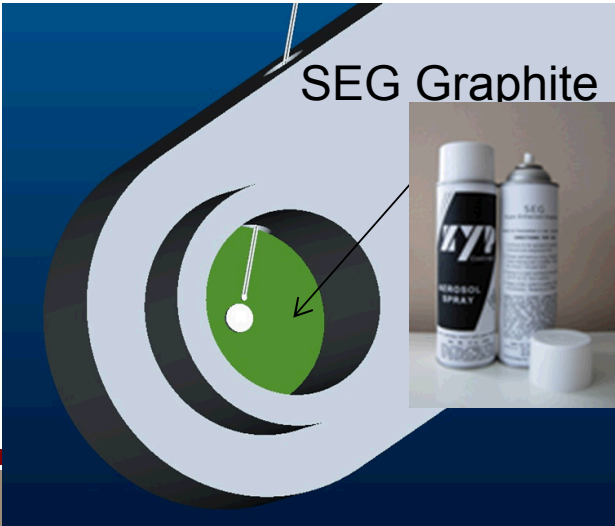
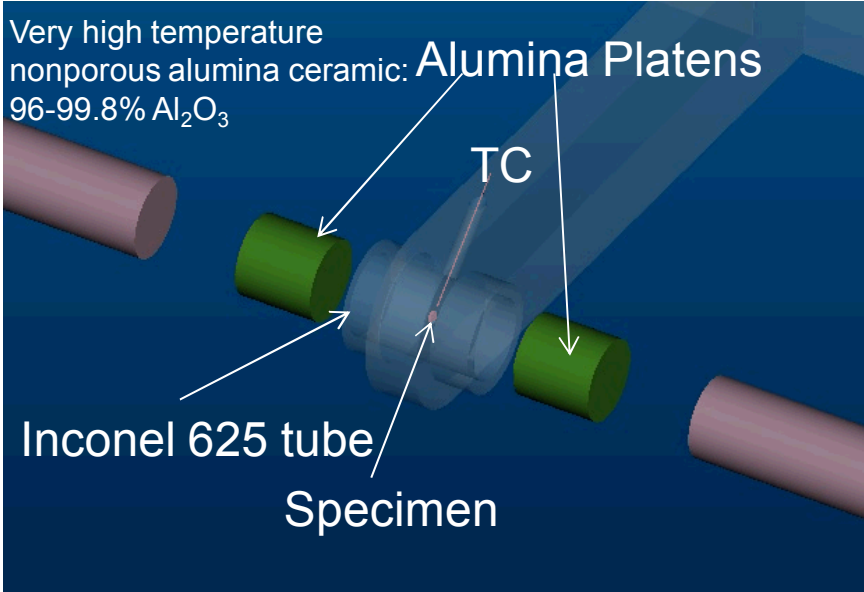
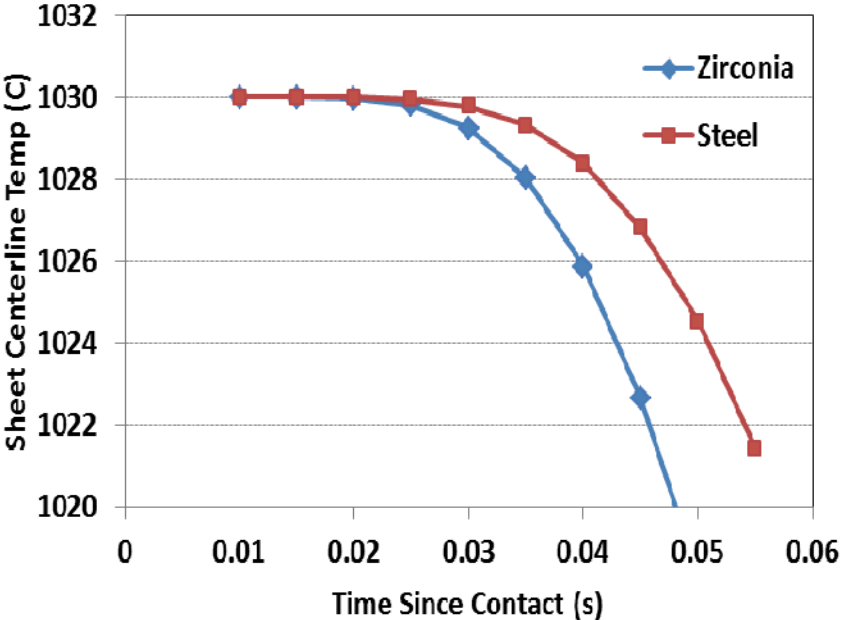
# Additional Challenges for High-Temperature Kolsky Bar Testing of Iridium

- Small/Thin Iridium Specimen
  - Temperature drops very quickly when the specimen starts in contact with cold pressure bars

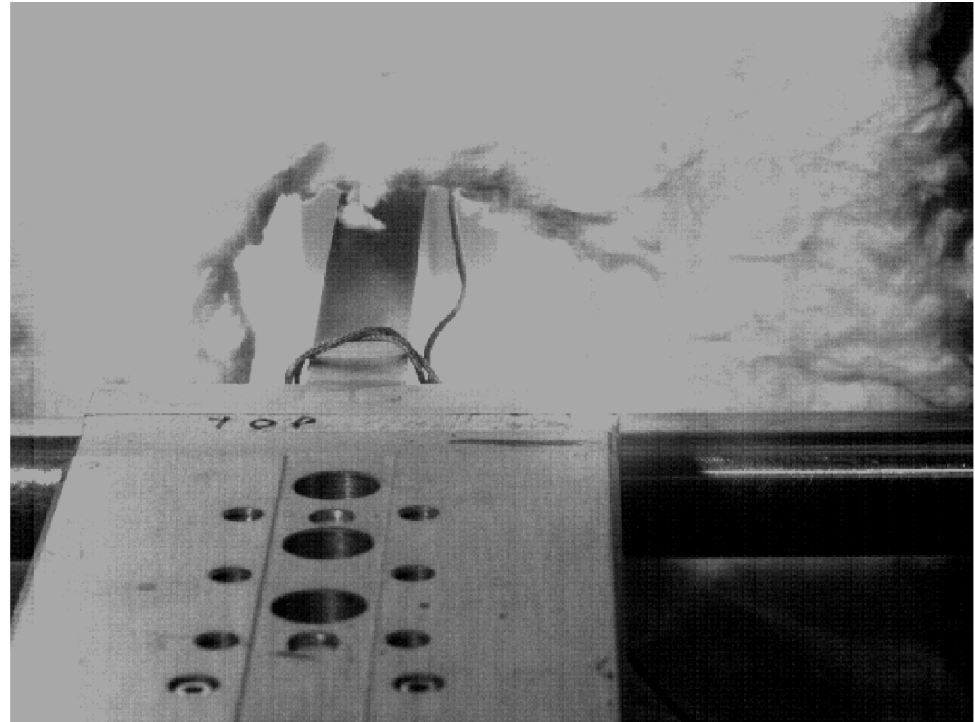
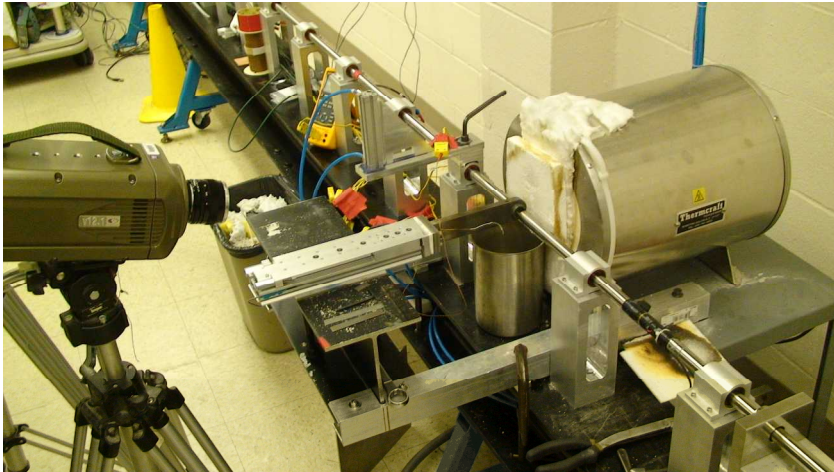


- High strength at high temperature
- High-Temperature Lubrication

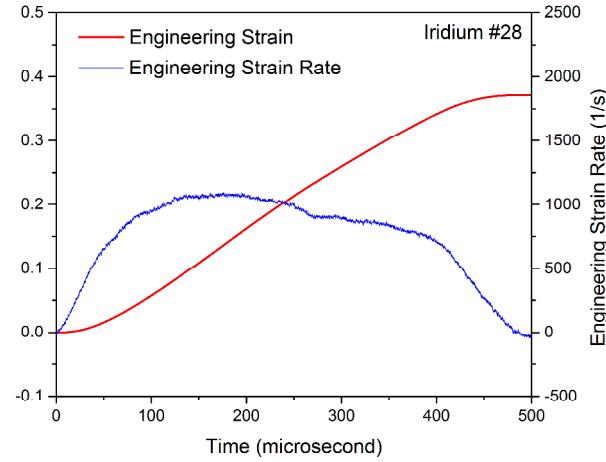
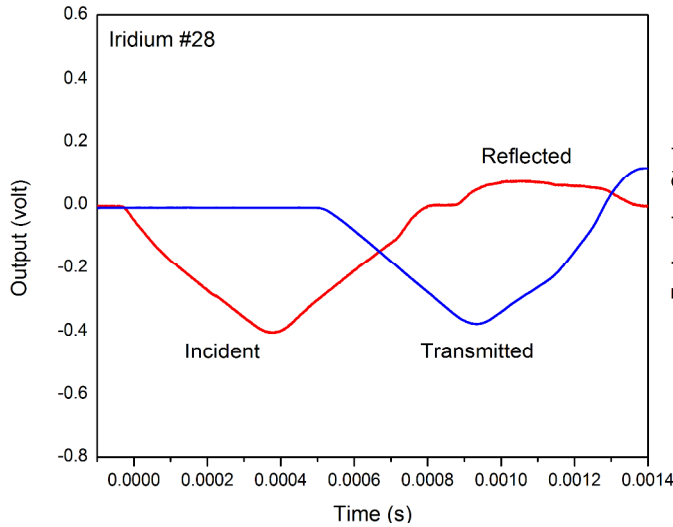
# Modified Sandwich Specimen Structures



# Experimental Setup and Procedure

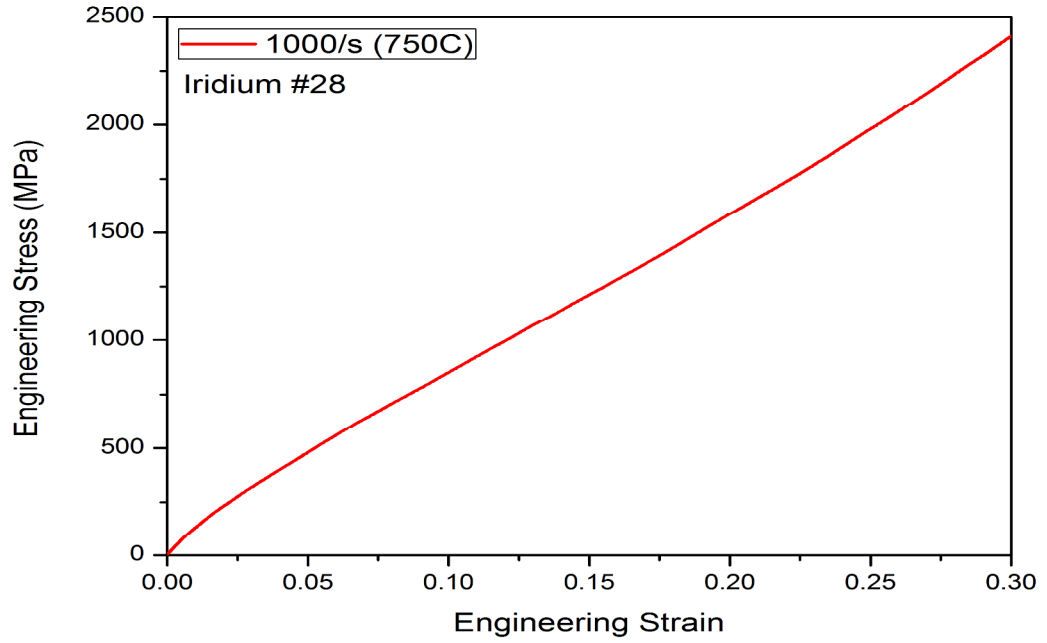
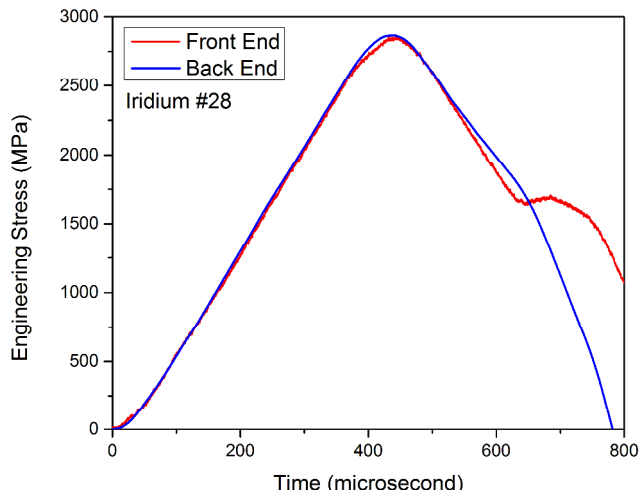


# Compression Test at 1000 s<sup>-1</sup>/750C



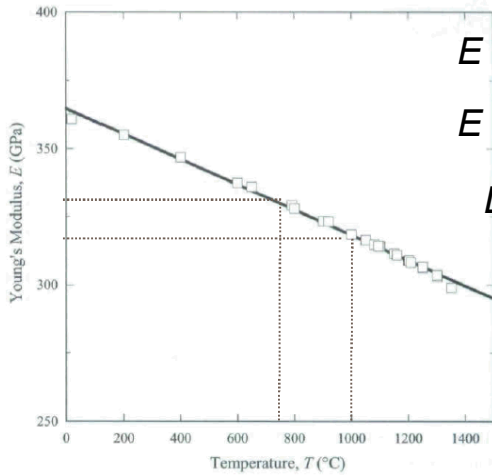
$$\dot{\epsilon} = \frac{u_1 - u_2}{l_0} = \frac{C_0}{l_0} (\epsilon_i - \epsilon_r - \epsilon_t)$$

$$\epsilon = \int_0^t \dot{\epsilon}(\tau) d\tau$$



$$\sigma_1 = \frac{A_b}{A_0} E_b (\epsilon_i + \epsilon_r) \quad \sigma_2 = \frac{A_b}{A_0} E_b \epsilon_t$$

# Diagnostic Uncertainties (Effect of Alumina Platens)



Wave (mechanical Impedance):  $\rho C$  or  $\sqrt{\rho E}$

- Alumina:  $3.6 \times 10^7 \text{ kg/m}^2/\text{s @ } 750\text{C}$   
 $3.5 \times 10^7 \text{ kg/m}^2/\text{s @ } 1000\text{C}$
- Steel bar:  $4.0 \times 10^7 \text{ kg/m}^2/\text{s (RT)}$

*Mechanical impedance mismatch is insignificant*

@ 30% strain  $\sigma = 2400 \text{ MPa}$   $F = 17000 \text{ N}$

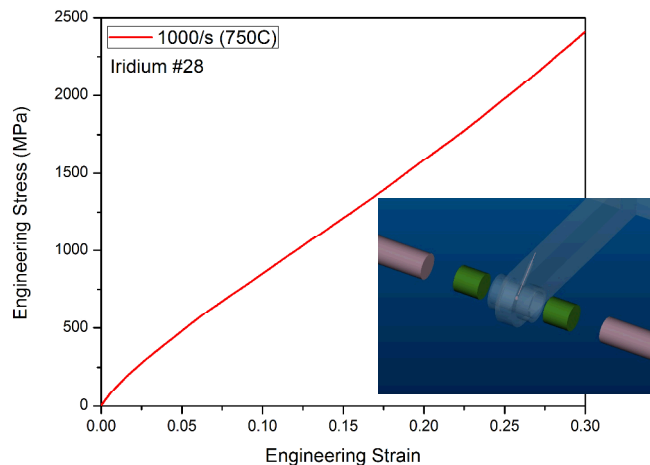
Alumina platens  $\sigma = 60 \text{ MPa}$   $\epsilon = 0.00018$

$$\delta = 0.00018 \times 19.05 \times 2 = 0.0069 \text{ mm}$$

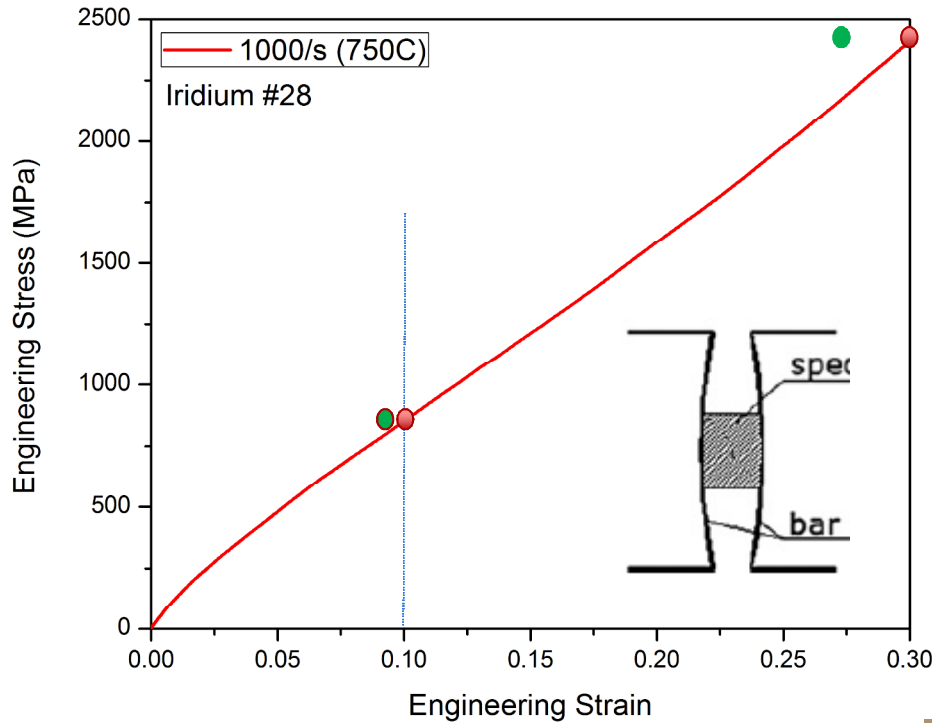


$$\epsilon_\delta = \frac{0.0069}{0.65} \approx 0.01$$

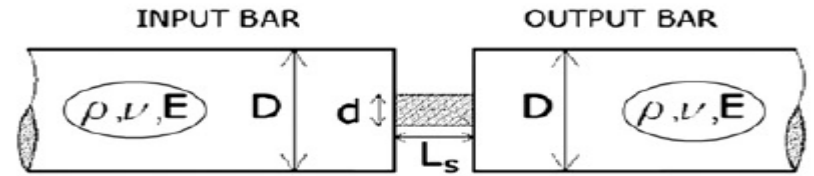
$$\Delta = \frac{\epsilon_\delta}{\epsilon} = \frac{0.01}{0.3} = 3.3\%$$



# Diagnostic Uncertainties



Safa & Gary, 2010:



$$\epsilon(t) = \epsilon_{SHPB}(t) - \epsilon_{punch.}(t)$$

$$\epsilon_{punch} = 2K_p \frac{\sigma_{SHPB} S_s}{l_s} \quad K_p = \frac{16}{3\pi^2} \frac{1-\nu^2}{dE} H_p \left( \frac{d}{D} \right)$$

$$H_p(x) = 2 - \left(x + \frac{1}{x}\right)E(x) - \left(x - \frac{1}{x}\right)K(x)$$

$$E(x) = \int_0^{\frac{\pi}{2}} \sqrt{1 - x^2 \sin^2 \theta} d\theta, \quad K(x) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - x^2 \sin^2 \theta}}$$

At 30%,  $d = d_0 \sqrt{\frac{1}{1-\epsilon}} = 3.586 \text{ mm}$

$$\frac{d}{D} = 0.188 \quad H_p \approx 1.578$$

$$\nu = 0.5$$

$$E = 330 \text{ GPa}$$

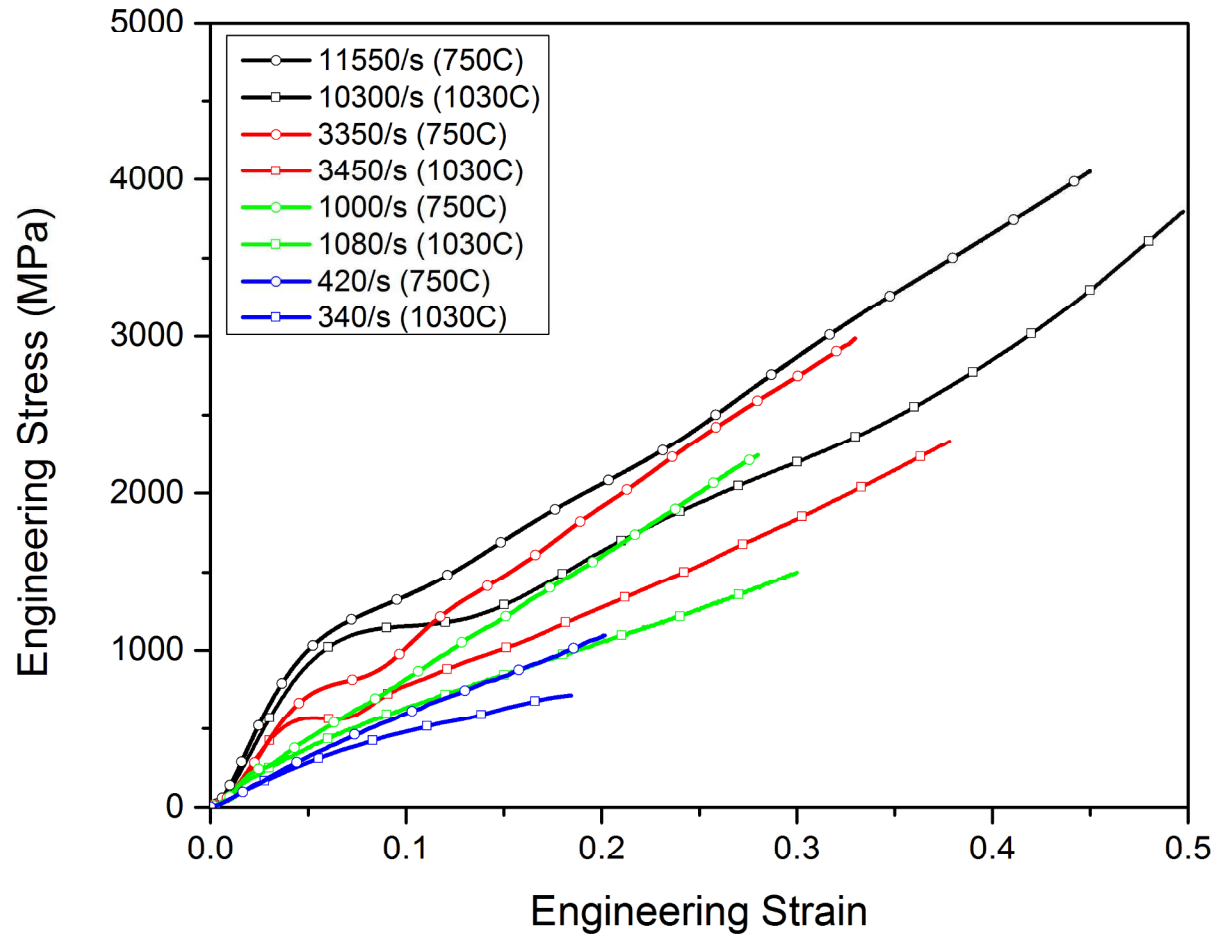
$$\epsilon_{punch} = 0.028$$

$$\Delta = \frac{\epsilon_{punch}}{\epsilon} = \frac{0.028}{0.3} = 9.3\%$$

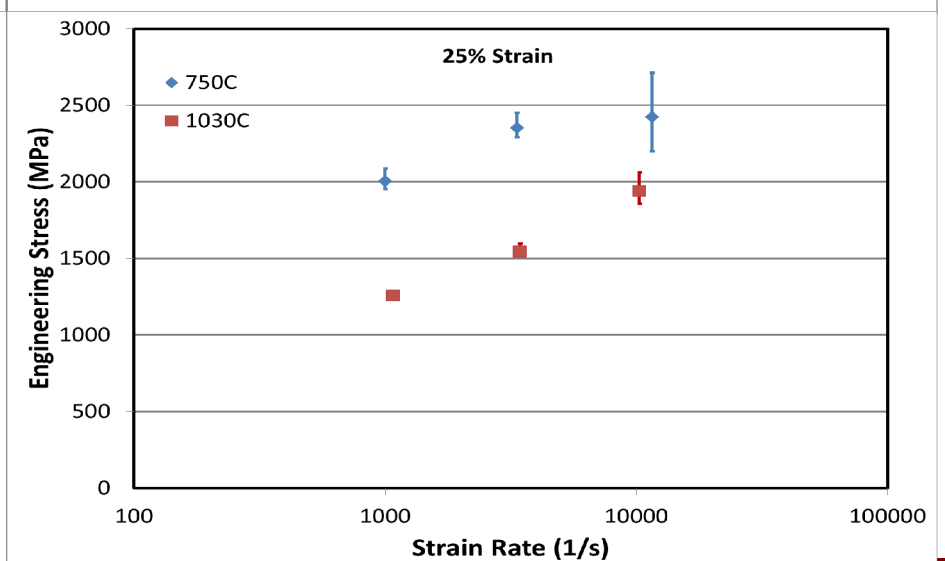
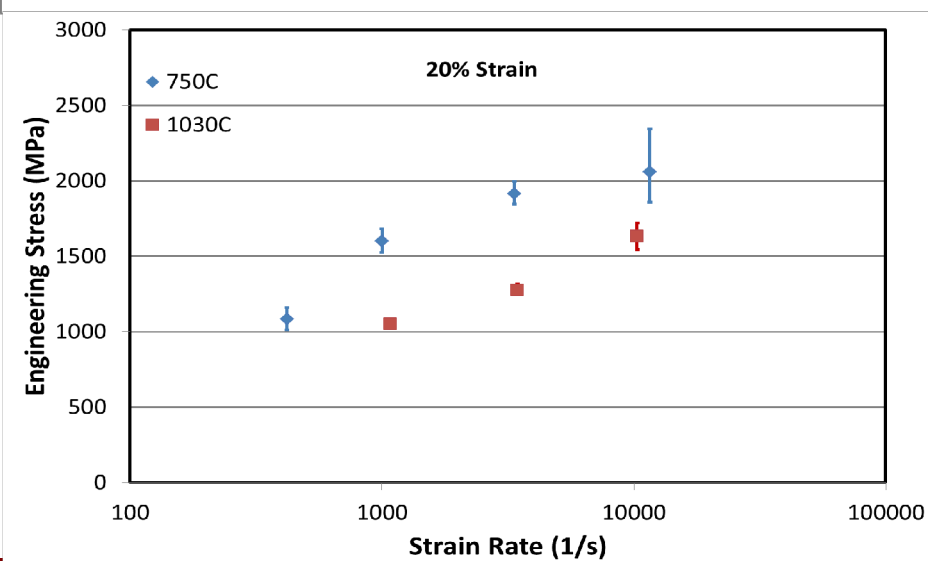
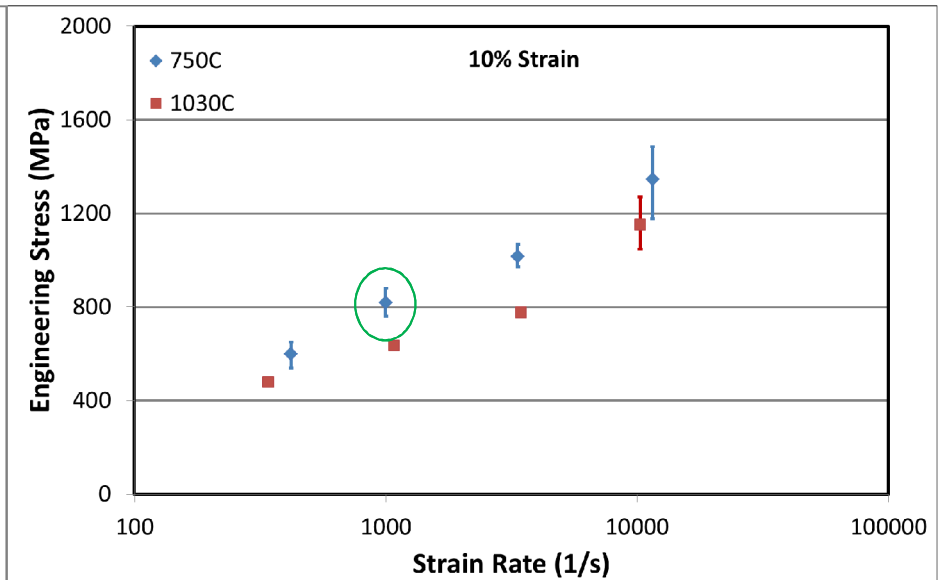
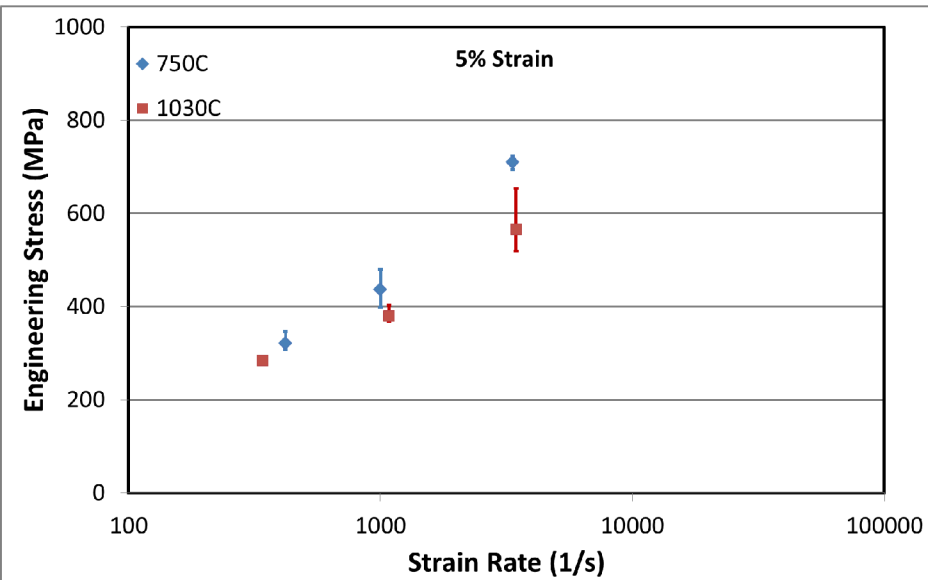
At 10%,  $\epsilon_{punch} = 0.0109$

$$\Delta = \frac{\epsilon_{punch}}{\epsilon} = \frac{0.0108}{0.1} = 10.8\%$$

# Engineering Stress-Strain Curves at Different Strain Rates and Temperatures

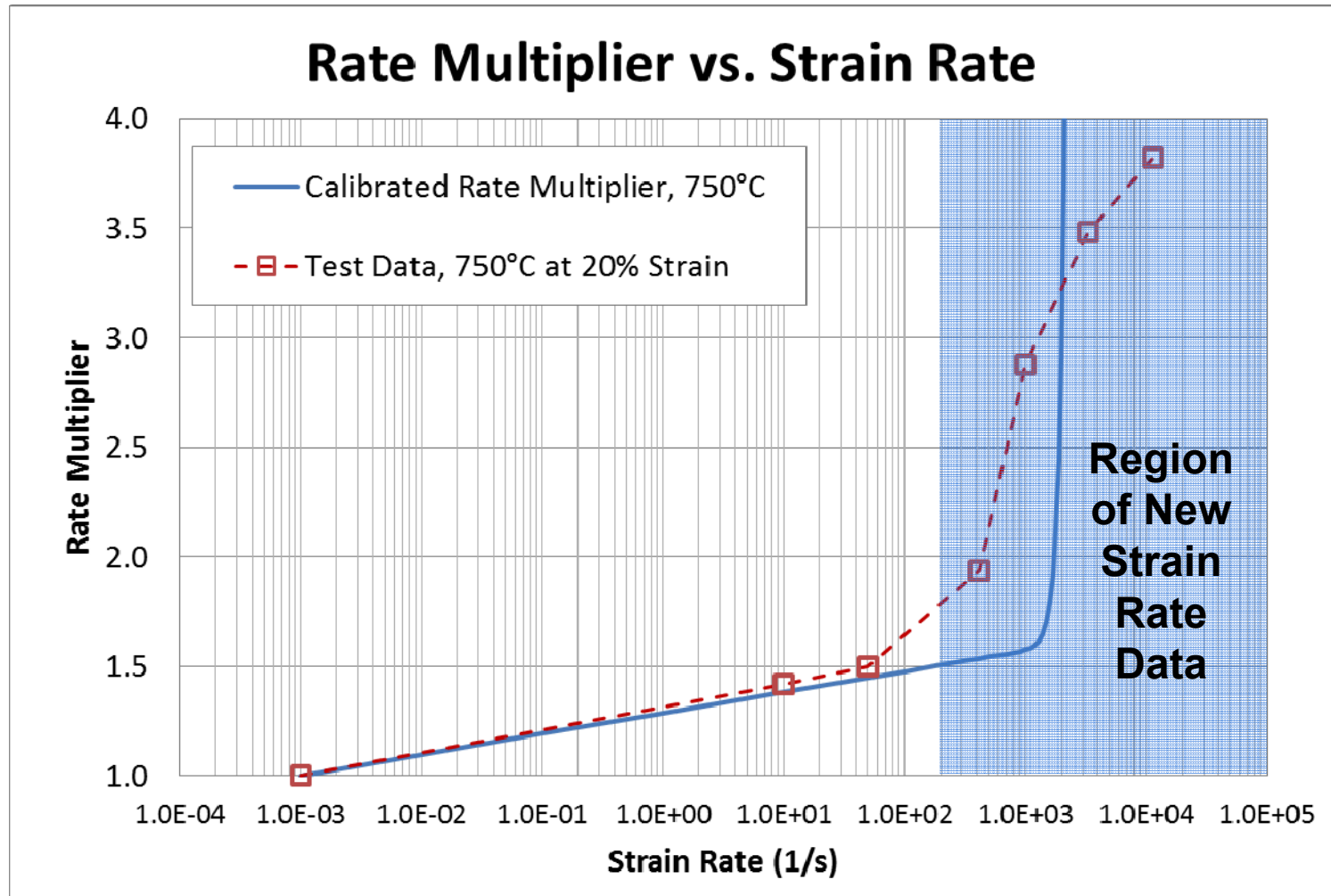


# Strong Strain-Rate and Temperature Effects



# Improved Modeling with Dynamic Data

(by courtesy of John Bignell)



# Summary

- Kolsky compression bar (split Hopkinson pressure bar) has been properly modified to characterize Iridium in compression at high temperatures
  - *Key Issues*
    - *Heat transfer from specimen to the bars*
    - *Uncertainty/error analysis*
    - *High ductility and strength of Iridium at very high temperatures*
    - *High-temperature interface lubrication*
- Dynamic compressive stress-strain curves of iridium have been obtained at
  - *Different strain rates (~400, 1000, 3000, 10000 per second)*
  - *Different temperatures (750 and 1030 C)*
- The compressive response of iridium is very sensitive to
  - *Strain rate*
  - *Temperature*

# Acknowledgments

*This work was sponsored by U.S. DOE Office of Space and Defense Power Systems (NE-75).*

- Ryan Bechtel, *U.S. Department of Energy*
- Ron Lipinski (6223), *Sandia RTG-Nuclear Launch Safety Program Manager*
- John Bignell (6233)
- Kevin Nelson (8256)
- Jeff Smith (1555)
- George Ulrich, *Oak Ridge National Laboratories*
- Easo George, *Oak Ridge National Laboratories*

*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.*

*Oak Ridge National Laboratory is a multi-program research laboratory managed by UT-Battelle, LLC, for the U.S. DOE under contract DE-AC05-00OR22725.*

# R&D Activities and Achievement (2013- )

- **Publications**

- 3 peer-reviewed journal papers (1 published; 2 under review)
- 9 conference abstracts/extended abstracts/papers

- **Professional Services**

- Journal reviewers: for ~30 international journals (past 6 years)
- Chair, Dynamic Behavior of Materials Technical Division, Society for Experimental Mechanics
- International Conference Organizers
  - Track organizer, session organizer, chairs at 2013 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, June 3-5, 2013, Lombard, Illinois, USA.
  - Track organizer, session organizer, chairs at 2014 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, June 2-5, 2014, Greenville, South Carolina, USA.
  - Scientific Committee Member and Session organizer at 16<sup>th</sup> International Conference on Experimental Mechanics (ICEM16), July 7-11, 2014, Cambridge, UK
  - International Conference Co-Chairman, scientific committee member at 2014 SEM Fall Conference, October 19-22, 2014, Beijing, China.
- External Proposal reviewers (for DoD and Universities)

- **External Collaboration**

- University of North Texas

("Laser based high-rate high-resolution displacement measurements for Kolsky bar tests")<sub>17</sub>