HYPERVELOCITY IMPACT SOCIETY

Symposium Program

HVIS

13th Hypervelocity Impact Symposium

April 26–30, 2015 | Boulder, Colorado

Missouri S&T | Missouri University of Science and Technology

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Welcome to the 13th HVIS 2015 Symposium

David E. Lambert, PhD
President
Hypervelocity Impact Society

The Hypervelocity Impact Society welcomes you to our pinnacle event - the 2015 Hypervelocity Impact Symposium (HVIS 2015). This is the 13th time we have held this forum to advance science and technology on hypervelocity impact phenomena and related technical areas.

HVIS 2015 continues our long-standing international venue for the discussion, interchange, presentation and recognition of technical contributions to the field. The technical quality of the papers continues to be very high with a diversity of topics ranging from Armor and Ballistic Technology to Equation of State to Spacecraft Debris and Shielding. This year, a special Plenary Session on Planetary Impact and Asteroid Defense is arranged to concentrate on a key area of our Societies’ objectives. Your HVIS Board of Directors and the Committees have worked hard to bring a high-quality, rewarding science forum to the beautiful City of Boulder, Colorado. I especially wish to thank the Symposium Committee and Technical Chairs for their diligence and time spent in preparing HVIS 2015, its social activities, Companion Program, and online Procedia Proceedings that are available.

Lastly, congratulations! You now have membership in HVIS from now until HVIS 2017 which will be held in the Spring of 2017 at the University of Kent, Canterbury, UK. Be sure to visit your Society website at www.hvis.org and please do not hesitate to let us know if you wish to volunteer on one of the many committees.

Thank you and enjoy your week.

David E. Lambert, PhD
President of Hypervelocity Impact Society

Welcome to HVIS 2015

Welcome to the 2015 Hypervelocity Impact Symposium! This is the 13th symposium in the most recent series of symposia devoted to the study of hypervelocity impact phenomena and related technologies. The technical papers presented this week reaffirm the society's commitment to providing a forum for the continued interaction of international scientists, engineers, and industrialists. Our objective this week is to facilitate the discussion and exchange of technical information related to hypervelocity impact phenomenology.

The presentations of the Distinguished Scientist Award recipient and the Society's Best Paper Award reinforce the society's commitment to recognize and encourage excellence and quality in our fields of endeavor. The plenary session presentations and the symposium banquet's keynote address are also indicative of the broad range of interests held by society members. The excellent technical program and commercial exhibits of this symposium present an outstanding opportunity for everyone to be enriched by one another's expertise.

The presentations of the Distinguished Scientist Award recipient and the Society's Best Paper Award reinforce the society's commitment to recognize and encourage excellence and quality in our fields of endeavor.

Learn about and discuss the latest technical work in a wide variety of subject areas, network with your colleagues, make new friends, renew acquaintances, shop and compare the latest in impact-related equipment, software capabilities, and services offered by the companies in the Exhibit Hall – you are encouraged to take advantage of all this symposium has to offer. Also, please take a moment to visit with this year's cohort of Alex Charters Student Scholars. These fine young men and women are our future – please congratulate them on their selection this year and offer them your support and encouragement as future hypervelocity impact scientists and engineers.

We would like to take a moment to thank the following individuals and groups who volunteered their time and expertise to make this symposium a reality: the hypervelocity impact society board of directors, society committee chairs and committee members, the technical program co-chairs, and the members of the HVIS 2015 technical program committee. Without your hard work, this symposium would not have been possible. The society thanks each of you for enriching our symposium with your presence and participation.

Enjoy your stay in Boulder, and please do take the time to visit some of the local attractions. We are looking forward to personally meeting and greeting many of you throughout the next few days.

William Schonberg
Timothy Maclay
HVIS 2015 Symposium Co-Chairs

William Schonberg
HVIS 2015 Co-Chair

Timothy Maclay
HVIS 2015 Co-Chair

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DISTANCE & CONTINUING EDUCATION

HVIS 2015 is coordinated by Missouri University of Science and Technology's Distance and Continuing Education (DCE) Office. DCE offers full-service event planning and coordinates national and international technical conferences, symposiums and seminars. For your next event, contact DCE.

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Phone: (573) 341-6222
Web: dce.mst.edu
Mail: 216 Centennial Hall
300 West 12th Street
Rolla, MO 65409-1560

Exhibitors

Stop by the Exhibit Hall *(Xanadu III)* during the Symposium to visit with vendors about the latest in impact-related equipment, services and software capabilities.

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Schedule at a Glance

all technical sesions held in Xanadu I & II

Sunday, April 26

3:00 pm Registration & Welcome Reception
Great Room

Monday, April 27

7:00 am Registration & Breakfast
8:00 am Opening Ceremonies - *Xanadu I & II*
8:40 am Distinguished Scientist Keynote Address
9:30 am Break/Exhibit Hall - *Xanadu III*
9:50 am **Technical Session 1:**
High-Velocity Penetration Mechanics and Target Response
Session Chairs: William Reinhart & Tim Holmquist
11:50 am Lunch/Visit Exhibit Hall - *Xanadu I & II*
1:10 pm **Technical Session 2:**
Hypervelocity Phenomenology Studies
Session Chair: Yasuhiro Akahoshi
2:50 pm Break/Exhibit Hall - *Xanadu III*
3:10 pm **Technical Session 3:**
Material Response *(including EOS)*
Session Chair: Brian Jensen
5:10 pm Technical Sessions End
5:30 pm Dinner & Entertainment at Rembrandt Yard
- 1301 Spruce St., Boulder, Colorado

Tuesday, April 28

7:00 am Registration & Breakfast
8:00 am **Plenary Session I** - *Xanadu I & II*
Speaker: Keith Jamison
8:40 am **Technical Session 4:**
Spacecraft Meteoroid/Debris Shielding and Failure Analyses I
Session Chair: Eric Christiansen
10:20 am Break/Exhibit Hall - *Xanadu III*
10:30 am **Poster Session** - *Fandango & Calypso*
12:10 pm Lunch - *on your own*
1:30 pm **Accelerator Technical Tour**
- University of Colorado
(advanced sign-up required)
5:00 pm Dinner - *on your own*

Wednesday, April 29

7:00 am Registration & Breakfast
8:00 am **Plenary Session II** - *Xanadu I & II*
Speaker: Michael Squire
8:40 am **Technical Session 5:**
Fracture and Fragmentation
Session Chairs: Nitta Kumi & Joel Williamsen
10:20 am Break/Exhibit Hall - *Xanadu III*
10:30 am **Technical Session 6:**
Armor/Anti-Armor and Ballistic Technology
Session Chairs: Scott Hill & Ernest Baker
12:10 pm Lunch/Visit Exhibit Hall - *Xanadu I & II*
Board of Directors Working Lunch - *Bastille Suite, 2nd floor*
1:30 pm **Technical Session 7:**
Analytical and Numerical Methodologies
Session Chair: Steve Evans
3:30 pm Break/Exhibit Hall - *Xanadu III*
3:50 pm **Technical Session 8:**
High-Velocity Launchers and Diagnostics
Session Chairs: Kevin Poorman & Jason Loiseau
5:10 pm Technical Sessions End
6:30 pm Symposium Banquet Dinner - *Xanadu I & II*
Speaker: Russell "Rusty" Schweickart

Thursday, April 30

7:00 am Registration & Breakfast
8:00 am **Plenary Session III** - *Xanadu I & II*
Speaker: William Ailor
8:40 am **Asteroid Impact/Planetary Defense Poster Session**
- Fandango & Calypso
8:40 am **Technical Session 9:**
Spacecraft Meteoroid/Debris Shielding
and Failure Analyses II
Session Chairs: Martin Sauer & William Bohl
10:20 am Break/Exhibit Hall - *Xanadu III*
10:30 am **Technical Session 10:**
Asteroid Impact and Planetary Defense Technology I
Session Chair: Mark Boslough
12:10 pm Lunch/Business Meeting - *Xanadu I & II*
1:30 pm **Technical Session 11:**
Asteroid Impact and Planetary Defense Technology II
Session Chair: Tarabay Antoun
3:30 pm **Panel Discussion:** Astroid Impact and Planetary Defense
4:30 pm Symposium Closes

Organizing Committee

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Ernest Baker, *Army Research Laboratory*
Kevin Poorman, *University of Denver Research Institute*
Jason Loiseau, *McGill University*

Symposium Schedule

Sunday Afternoon, April 26, 2015

3:00 pm – 5:00 pm
Registration and Welcome Reception
Great Room, St. Julien Hotel & Spa

Monday Morning, April 27, 2015 | Xanadu I & II | *Session Abstracts pp 15-17*

7:00 am – 8:00 am
Registration & Breakfast

8:00 am – 8:40 am
Opening Ceremonies

8:40 am – 9:30 am
Distinguished Scientist Keynote Address

9:30 am – 9:50 am
Break/Exhibit Hall - *Xanadu III*

9:50 am – 11:50 am
Technical Session 1:
High-Velocity Penetration Mechanics and Target Response

11:50 am – 1:10 pm
Lunch - *Xanadu I & II*

Visit Exhibit Hall - *Xanadu III*

Technical Session 1 | 9:50 am – 11:50 am | Xanadu I & II

High-Velocity Penetration Mechanics and Target Response

Session Chairs: William Reinhart and Tim Holmquist

71 – Concurrent Velocimetry and Flash X-ray Characterization of Impact and Penetration in an Armor Ceramic
Brian E. Schuster, Brady B. Aydelotte, R. Brian Leavy, Sikhanda Satapathy, Michael B. Zellner, *U.S. Army Research Laboratory, USA*

47 – Simulation and Experiments of Hypervelocity Impact in Containers with Fluid and Granular Fillings
Pascal Matura, *Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institute*; Georg Heilig, Martin Lueck, Martin Sauer, *Germany*

49 – Kinetic Energy Required for Perforating Double Reinforced Concrete Targets: A Parametric Numerical Study Considering Impact Velocity and Penetrator Presented Area
Christopher S. Meyer, *U.S. Army Research Laboratory, USA*

73 – High-Velocity Impact of Encased Al/PTFE Projectiles on Structural Aluminum Armor
Brett Sorensen, *Army Research Laboratory, USA*

58 – Modeling Plastic Deformation of Steel Plates in Hypervelocity Impact Experiments
Brendan O'Toole, *University of Nevada-Las Vegas and National Security Technologies*; Mohamed Trabia, Robert Hixson, Shawoon K. Roy, Michael Pena, Steven Becker, Edward Daykin, Eric Machorro, Richard Jennings, Melissa Matthes, *USA*

85 – Shaped Charge Jet Penetration of Alon® Ceramic Assessed by Proton Radiography and Computational Simulations
Michael Zellner, *U.S. Army Research Laboratory and Los Alamos National Laboratory*; Richard Becker, Dattatraya Dandekar, Richard Leavy, Parimal Patel, *PRad Team, USA*

Symposium Schedule

Monday Afternoon, April 27, 2015 | Xanadu I & II | *Session Abstracts pp 17-19*

1:10 pm – 2:50 pm
Technical Session 2:
Hypervelocity Phenomenology Studies

2:50 pm – 3:10 pm
Break/Exhibit Hall - *Xanadu III*

3:10 pm – 5:10 pm
Technical Session 3:
Material Response

5:10 pm
Technical Sessions End

5:30 pm – 8:30 pm
Dinner & Entertainment
at Rembrandt Yard
- 1301 Spruce St., Boulder, Colo.

Technical Session 2 | 1:10 pm – 2:50 pm

Hypervelocity Phenomenology Studies

Session Chair: Yasuhiro Akahoshi

34 – Hypervelocity Pressure Fields Driven by Cylindrical Converging Shock Used for Accelerating Dense Metal Particles
Charles Jenkins, *Air Force Research Laboratory, Munitions Directorate;* Robert Ripley, Chris Cloney, *USA*

39 – Control of Shaped Charge Jets Through Non-uniform Confinement
Geremy Kleiser, *Air Force Research Laboratory, Munitions Directorate;* David Lambert, *USA*

54 – Hypervelocity Penetration into Soil
Nicholas Nechitailo, *Naval Surface Warfare Center, USA*

79 – Emission Spectroscopy of Hypervelocity Impacts on Aluminum, Organic and High-Explosive Targets
Jimmy Verreault, *TNO;* James Day, Wouter Halswijk, Jason Loiseau, Justin Huneault, Andrew J. Higgins, Adam D. Devir, *The Netherlands, Canada and Israel*

80 – The Vaporization Threshold: Hypervelocity Impacts of Ice Grains Into a Titanium Cassini Spacecraft Instrument Chamber
James D. Walker, *Southwest Research Institute;* Sidney Chocron, J. Hunter Waite, Timothy Brockwell, *USA*

Technical Session 3 | 3:10 pm – 5:10 pm

Material Response

Session Chair: Brian Jensen

45 – Simulation-Based Study of Layered Aluminum Crystal Microstructures Subjected to Shock Loading
Jeffrey Lloyd, *Impact Physics, RDRL-WMP-C, US Army Research Laboratory, Aberdeen Proving Ground;* John Clayton, *USA*

66 – Shock Wave Structure in Particulate Composites
Michael Rauls, *California Institute of Technology;* Guruswami Ravichandran, *USA*

19 – The Unifying Role of Dissipative Action in the Dynamic Failure of Solids
Dennis Grady, *Applied Research Associates, USA*

16 – Impact Compaction of a Granular Material
Gregg Fenton, *Applied Research Associates;* Blaine Asay, Devon Dalton, *USA*

7 – Guided Impact Mitigation in 2D and 3D Granular Crystals
Hayden Burgoyne, *Caltech;* John Newman, Wade Jackson, Chiara Daraio, *USA*

31 – Strength of Granular Materials in Transient and Steady State Rapid Shear
Ryan Hurley, *California Institute of Technology;* José Andrade, *USA*

Symposium Schedule

Tuesday Morning April 28, 2015 | Xanadu I & II | *Session Abstracts pp 19-21*

7:00 am – 8:00 am
Registration & Breakfast

8:00 am – 8:40 am
Plenary Session I
Speaker: Keith Jamison

8:40 am – 10:20 am
Technical Session 4: Spacecraft Meteoroid/ Debris Shielding and Failure Analyses I

10:20 am – 10:30 am
Break/Exhibit Hall - *Xanadu III*

10:30 am – 12:10 pm
Poster Session - *Fandango & Calypso*

12:10 pm – 1:30 pm
Lunch - *on your own*

1:30 pm – 5:00 pm
Accelerator Technical Tour - *University of Colorado*

5:00 pm
Dinner - *on your own*

Technical Session 4 | 8:40 am – 10:20 am

Spacecraft Meteoroid/Debris Shielding and Failure Analyses I

Session Chair: Eric Christiansen

10 – Toughened Thermal Blanket for Micrometeoroid and Orbital Debris Protection
Eric Christiansen, *NASA Johnson Space Center;* Dana Lear, *USA*

13 – MMOD Puncture Resistance of EVA Suits with Shear Thickening Fluid (STF) — Armor™ Absorber Layers
Colin Cwalina, *Department of Chemical and Biomolecular Engineering, University of Delaware;* Richard Dombrowski, Charles McCutcheon, Eric Christiansen, Norman J. Wagner, *USA*

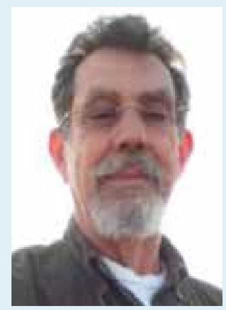
48 – Numerical Investigations of Hypervelocity Impacts on Pressurized Aluminum-Composite Vessels
Jérome Mespoulet, *Thiot Ingenierie;* Fabien Plassard, Pierre-Louis Héreil, Patrick Thiot, *France*

72 – Effects of Debris Cloud Interaction with Satellites Critical Equipments - Experiments and Modeling
Jean-Marc Sibeaud, *CEA DAM, GRAMAT;* Christian Puillet, *France*

24 – Hypervelocity Impact of Aluminum Projectiles Against Pressurized Aluminum-Composite Vessel
Pierre-Louis Héreil, *Thiot Ingenierie;* Jérome Mespoulet, Fabien Plassard, *France*

Plenary Speaker

Tuesday, April 28, 2015
8:00 am – 8:40 am



Keith Jamison
SAIC/Air Force Research Laboratory
Eglin Air Force Base, Florida

Presentation Title:
Development of a Diagnostic Technique to Track Magnetized

Presenter Bio: Keith Jamison is a product of Kansas upbringing, perusing both undergraduate and graduate degrees at Kansas State University. He received his PhD in 1978 in the field of atomic physics of ion-atom collisions. Upon graduation, he began his professional career as an experimental physicist at Aberdeen Proving Ground at the U.S. Army Ballistic Research Laboratory. His early work focused on development of diagnostics for plasma armature railguns, firing his first railgun in August of 1980. His studies soon expanded to include a number of alternatives in electric energy launchers, pulsed power supplies and systems studies forecasting the utility of electric guns. In 1988, he joined SAIC and began a long tenure at Eglin AFB first working for the Strategic Defense Initiative Organization (SDIO) railgun program and later in conventional munitions for the Air Force. He was awarded the Peter Mark Medal for Outstanding contributions to electromagnetic launch technology in 1998. Today, he continues his work as an experimental physicist with SAIC at the Air Force Research Laboratory on Eglin AFB.

Symposium Schedule

Wednesday Morning, April 29, 2015 | Xanadu I & II | *Session Abstracts pp 21-23*

7:00 am – 8:00 am
Registration & Breakfast

8:00 am – 8:40 am
Plenary Session II
Speaker: Michael Squire
- *Xanadu I & II*

8:40 am – 10:20 am
Technical Session 5:
Fracture and Fragmentation

10:20 am – 10:30 am
Break/Exhibit Hall - *Xanadu III*

10:30 am – 12:10 pm
Technical Session 6:
Armor/Anti-Armor and Ballistic Technology

12:10 pm – 1:30 pm
Lunch - *Xanadu I & II*
Board of Directors Working Lunch
- *Bastille Suite, 2nd floor*

Accelerator Technical Tour

University of Colorado

Tuesday April 28
1:30 pm - 5 pm

The Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT) houses a 3 MV linear electrostatic dust accelerator which is used for a variety of impact research activities, as well as calibrating dust instruments for space applications. The dust accelerator is equipped with a 3 MV Pelletron generator capable of accelerating micron and submicron particles of various materials to velocities approaching 100 km/s.

Plenary Speaker

Wednesday, April 29, 2015
8:00 am – 8:40 am

Michael Squire
Principal Engineer, NASA Engineering and Safety Center

Presentation Title:

NASA's Needs and Trends in Hypervelocity Impact Modeling, Testing and Technology

Presenter Bio: Mr. Michael Squire currently serves as a Principal Engineer in the NASA Engineering and Safety Center (NESC). In 1991, Mr. Squire began his career at the Kennedy Space Center as a Space Shuttle Systems Engineer responsible for the testing and check-out of the Environmental Control and Life Support System for the Space Shuttle. In 1995, he assumed the added responsibility for the Fuel Cell and Power Reactant Storage and Distribution System (FC/PRSD). In 2002, Mr. Squire was named the System Specialist for the FC/PRSD System, where he served as the lead engineer responsible for ground processing of the FC/PRSD System. In 2006, Mr. Squire joined the NESC as the Technical Assistant to the NESC Director at the Langley Research Center. The following year, he was named as an NESC Associate Principal Engineer, where he directed multi-discipline teams for a number of technical assessments. These assessment activities included several focusing on the increasing threat of micrometeoroid and orbital debris (MMOD). He directed an evaluation of the Constellation Program's MMOD risk assessment process, providing recommendations on how to improve the Orion Crew Module's MMOD protection capability. In another activity, Mr. Squire led a team to develop enhanced MMOD shield designs for International Space Station modules. In 2009, Mr. Squire received the Silver Snoopy Award for his work on the investigation seeking the root cause of damage to the Space Shuttle orbiter's reinforced carbon-carbon wing leading edge. Mr. Squire holds a BS in Aerospace Engineering from the University of Colorado at Boulder.

Symposium Schedule

Wednesday Morning, April 29, 2015 | Xanadu I & II | *Session Abstracts pp 21-23*

Technical Session 5 | 8:40 am – 10:20 am

Fracture and Fragmentation

Session Chairs: Nitta Kumi and Joel Williamsen

5 – The Mechanochemistry of Damage and Terminal Ballistics
Todd Bjerke, *U.S. Army Research Laboratory, Aberdeen Proving Ground;* Michael Greenfield, Steven Segletes, *USA*

37 – Stress Wave and Damage Propagation in Transparent Materials Subjected to Hypervelocity Impact
Nobuaki Kawai, *Kumamoto University;* Syunske Zama, Wataru Takemoto, Kairi Moriguchi, Kazuyoshi Arai, Sunao Hasegawa, Eiichi Sato, *Japan*

41 – Incorporation of Material Variability in the Johnson Cook Model
Ryan Kupchella, *Corvid Technologies;* David Stowe, Xudong Xiao, Anne Algoso, John Cogar, *USA*

56 – Ejecta Cone Angle and Ejecta Size Following a Non-Perforating Hypervelocity Impact
Masahiro Nishida, *Nagoya Institute of Technology;* Yasuyuki Hiraiwa, Koichi Hayashi, Sunao Hasegawa, *Japan*

78 – A Quantitative Approach to Comparing High Velocity Impact Experiments and Simulations Using XCT Data
Andrew Tonge, *The Johns Hopkins University;* Brian Leavy, Jerry LaSalvia, K.T. Ramesh, Rebecca Brannon, *USA*

Technical Session 6 | 10:30 am – 12:10 pm

Armor/Anti-Armor and Ballistic Technology

Session Chairs: Scott Hill and Ernest Baker

3 – Impact and Penetration of SiC: The Role of Rod Strength in the Transition from Dwell to Penetration
Brady Aydelotte, *US Army Research Laboratory;* Brian Schuster, *USA*

77 – Method for Prediction of Fragment Impact Response Using Physics Based Modeling and Statistical Analysis
Justin Sweitzer, *CGI Federal;* Nicholas Peterson, *USA*

55 – Numerical Modelling of Ultra-High Molecular Weight Polyethylene Composite Under Impact Loading
Long Nguyen, *RMIT University;* Torsten Lässig, Shannon Ryan, Werner Riedel, Adrian Mouritz, Adrian Orifici, *Australia and Germany*

60 – Composite Material Particle Impact Mitigation Sleeve Testing
Nicholas Peterson, *US Army AMRDEC;* Justin Sweitzer, *USA*

44 – Investigations of High Performance Fiberglass Impact Using a Combustionless Two-Stage Light-Gas Gun
Leslie Lamberson, *Drexel University, USA*

Symposium Schedule

Wednesday Afternoon April 29, 2015 | Xanadu I & II | *Session Abstracts pp 23-24*

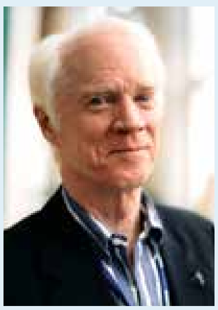
1:30 pm – 3:30 pm
Technical Session 7:
Analytical and Numerical Methodologies

3:30 pm – 3:50 pm
Break/Exhibit Hall - *Xanadu III*

3:50 pm – 5:10 pm
Technical Session 8:
High-Velocity Launchers and Diagnostics

5:10 pm
Technical Sessions End

6:30 pm – 8:30 pm
Symposium Banquet Dinner
Banquet Speaker:
Russell "Rusty" Schweickart
- *Xanadu I & III*



Banquet Speaker

Wednesday, April 29, 2015
6:30 pm – 8:30 pm

Russell "Rusty" Schweickart
Chairman of the Board, B612 Foundation

Presentation Title:

Uncertainty and Indecision: Geopolitical Implications in Planetary Defense

Abstract: The challenges of planetary defense are largely seen as technical in nature. Yet the ultimate societal response to challenges which are global in nature are often determined by non-technical issues. Planetary defense is just such an issue. While such a realization may be of interest, per se, the ultimate success of initial responses to NEO impact threats may lie in recognizing and accepting the geopolitical challenges and tailoring technical preparedness in anticipation of this realpolitik.

Presenter Bio: Russell L. (Rusty) Schweickart is a retired business and government executive and serves today as Chairman of the Board of the B612 Foundation, a non-profit organization that champions the development and testing of a spaceflight concept to protect the Earth from future asteroid impacts. Schweickart retired from ALOHA Networks, Inc. in 1998 where he served as President and CEO from 1996 through 1998. ALOHA was a data communications company specializing in high performance, wireless internet access equipment. He was formerly the Executive Vice President of CTA Commercial Systems, Inc. and Director of Low Earth Orbit (LEO) Systems where he led efforts in developing the GEMnet system, a second generation LEO communication satellite constellation designed to provide regular commercial electronic messaging services on a global basis. Prior to his CTA work Schweickart founded and was president of Courier Satellite Services, Inc., a global satellite communications company which developed LEO satellites to provide worldwide affordable data services. He has also worked extensively in Russia and the former Soviet Union on scientific and telecommunications matters.

Symposium Schedule

Wednesday Afternoon April 29, 2015 | Xanadu I & II | *Session Abstracts pp 23-24*

Technical Session 7 | 1:30 pm – 3:30 pm

Analytical and Numerical Methodologies

Session Chair: Steve Evans

64 – Analysis of Impact Melt and Vapor Production in CTH for Planetary Applications
Stephanie Quintana, *Brown University;* David Crawford, Peter Schultz, *USA*

42 – SPH Modeling Improvements for Hypervelocity Impacts
Ryan Kupchella, *Corvid Technologies;* David Stowe, Mark Weiss, Hua Pan, John Cogar, *USA*

50 – Analytic Ballistic Performance Model of Whipple Shields
Joshua Miller, *University of Texas at El Paso and NASA Johnson Space Center;* Michael Bjorkman, Eric Christiansen, Shannon Ryan, *USA and Australia*

76 – Improved Artificial Viscosity in Finite Element Method (FEM) for Hypervelocity Impact Calculations
David Stowe, *Corvid Technologies;* Ryan Kupchella, John Cogar, *USA*

67 – Support Vector Machines for Characterising Whipple Shield Performance
Shannon Ryan, *Defence Science and Technology Organisation;* Sewandi Kandanaarachchi, Kate Smith-Miles, *Australia and Singapore*

12 – Computational Modeling of Electrostatic Charge and Fields Produced by Hypervelocity Impact
David Crawford, *Sandia National Laboratories, USA*

Technical Session 8 | 3:50 pm – 5:10 pm

High-Velocity Launchers and Diagnostics

Session Chairs: Kevin Poorman and Jason Loiseau

29 – Benchmarking Surface Position from Laser Velocimetry with High-Speed Video in Impact Experiments
Marylesa Howard, *National Security Technologies;* Aaron Luttman, Eric Machorro, Rand Kelly, Jerome Blair, Melissa Matthes, Michael Pena, Michael Hanache, Brendan O'Toole, Nathan Sipe, Kristen Crawford, B. T. Meehan, Robert Hixson, *USA*

46 – The Analysis Technique for Ejecta Cloud Temperature Based on Atomic Spectrum
Zhao-xia Ma, *CARDC;* Jie Huang, An-hua Shi, Hua-yu Hu, LI Yi, Sen Liu, *P.R. China*

63 – EMI's TwinGun Concept for a New Light-Gas Gun Type Hypervelocity Accelerator
Robin Putzar, *Franhofer Institute for High-Speed Dynamics;* Earnst-Mach-Institut, EMI; Frank Schaefer, *Germany*

30 – Down-Bore Velocimetry of an Explosively Driven Light-Gas Gun
Justin Huneault, *McGill University;* Jason Loiseau, Myles Hildebrand, Andrew Higgins, *Canada*

Symposium Schedule

Thursday Morning April 30, 2015 | Xanadu I & II | *Session Abstracts pp 25-27*

7:00 am – 8:00 am
Registration & Breakfast

8:00 am – 8:40 am
Plenary Session III
Speaker: William Ailor
- *Xanadu I & II*

8:40 am – 10:20 am
Planetary Impact and Defense Poster Session
- *Fandango & Calypso*

8:40 am – 10:20 am
Technical Session 9:
Spacecraft Meteoroid/ Debris Shielding and Failure Analyses II

10:20 am – 10:30 am
Break/Exhibit Hall - *Xanadu III*

10:30 am – 12:10 pm
Technical Session 10:
Asteroid Impact and Planetary Defense Technology I

12:10 pm – 1:30 pm
Lunch/Business Meeting
- *Xanadu I & II*

Plenary Speaker

Thursday, April 30, 2015
8:00 am – 8:40 am

William Ailor
Principal Engineer, Center for Orbital and Reentry Debris Studies
The Aerospace Corporation

Presentation Title:

The Current State of Planetary Defense

Presenter Bio: Dr. William Ailor joined The Aerospace Corporation in 1974 and currently serves as the principal engineer for the Center for Orbital and Reentry Debris Studies (CORDS). During his tenure at Aerospace, he has spent 15 years conducting analyses on spacecraft reentry and reentry breakup. He has served as principal director of the Network Systems and Services Subdivision and led the evolution of Aerospace's email and network services. He worked in the Strategic Planning Office, where he helped develop Aerospace's first strategic plan. Dr. Ailor established and led the Space Hazards and Operations Support Directorate at Aerospace to prototype new capabilities for providing space situational awareness information to satellite operators. He is currently leading the development of the reentry breakup recorder, a small device that gathers data critical to understanding and minimizing hazards associated with reentering space hardware.

Dr. Ailor earned a bachelor's degree in aerospace engineering and a master's degree in mechanical engineering, both at the North Carolina State University. He earned his Ph.D. in aerospace engineering at Purdue University. Dr. Ailor has received the NASA Group Achievement Award three times. He has served on numerous panels, including on the Interagency Nuclear Safety Review Panels for the Galileo, Ulysses, Cassini, Mars Pathfinder, Mars Exploration Rover, and Mars Science Laboratory missions. He has also served as chair or co-chair for eight international conferences, including four on planetary defense.

Symposium Schedule

Thursday Morning April 30, 2015 | Xanadu I & II | *Session Abstracts pp 25-27*

Technical Session 9 | 8:40 am – 10:20 am

Spacecraft Meteoroid/Debris Shielding and Failure Analyses II

Session Chair: Martin Sauer and William Bohl

65 – Time-resolved Spectroscopy of Plasma Flash from Hypervelocity Impact on DebriSat
Gouri Radhakrishnan, *The Aerospace Corporation, USA*

75 – Investigation of S-SPH for Hypervelocity Impact Calculations
David Stowe, *Corvid Technologies;* Ryan Kupchella, Hua Pan, John Cogar, *USA*

57 – Response of a Wire Probe Antenna Subjected to Hyper-Velocity Impacts
Kumi Nitta, *Japan Aerospace Exploration Agency;* Masumi Higashide, Atsuhi Takeba, Masahide Katayama, *USA*

62 – Orbital Debris Assessment Testing in the AEDC Range G
Marshall Polk, *USAF;* David Woods, Brian Roebuck, John Opiela, Patti Sheaffer, Jer-Chyi Liou, *USA*

25 – Comparison of Aluminum Alloy and CFRP Bumpers for Space Debris Protection
Masumi Higashide, *Japan Aerospace Exploration Agency;* Takumi Kusano, Yuu Takayanagi, Kazuyoshi Arai, Sunao Hasegawa, *Japan*

Technical Session 10 | 8:40 am – 10:20 am

Asteroid Impact and Planetary Defense Technology I

Session Chair: Mark Boslough

26 – Momentum Transfer in Hypervelocity Impact Experiments on Rock Targets
Tobias Hoerth, *Fraunhofer EMI;* Frank Schäfer, Jan Hupfer, Oliver Millon and Matthias Wickert, *Germany*

27 – Dynamic Brittle Fragmentation: Probing the Byproducts of Hypervelocity Impact in Space
James Hogan, *Hopkins Extreme Materials Institute;* Charles El Mir, Jeffrey Plescia, KT Ramesh, *USA*

40 – Remnants of Early Archean Impact Deposits on Earth: Search for a Meteoritic Component in the BARB5 and CT3 Drill Cores (Barberton Greenstone Belt, South Africa)
Christian Koeberl, *University of Vienna;* Toni Schulz, Uwe Reimold, *Austria and Germany*

22 – Deep Impact – A Review of the World's Pioneering Hypervelocity Impact Mission
Monte Henderson, *Ball Aerospace;* William Blume, *USA*

74 – Modeling Momentum Transfer from Kinetic Impacts: Implications for Redirecting Asteroids
Angela Stickle, *Johns Hopkins University Applied Physics Laboratory*; Justin Atchison, Olivier. Barnouin, Andrew Cheng, David Crawford, Carolyn Ernst, Zachary Fletcher, Andy Rivkin, *USA*

Symposium Schedule

Thursday Afternoon April 30, 2015

Session Abstracts pp 28

1:30 pm – 3:30 pm
Technical Session 11:
Asteroid Impact and Planetary Defense Technology II

3:10 pm – 3:30 pm
Break/Exhibit Hall - *Xanadu III*

3:30 pm – 4:30 pm
Panel Discussion:
Astroid Impact and Planetary Defense

4:30 pm
Symposium Closes

Technical Session 11 | 1:30 pm – 4:30 pm

Asteroid Impact and Planetary Defense Technology II

Session Chair: Tarabay Antoun

9 – Facing a Hypervelocity Asteroid Impact Disaster: To Deflect or Evacuate?
Clark R. Chapman, *Dept. of Space Studies, Southwest Research Institute, USA*

86 – Orbital Simulations for Directed Energy Deflection of Near-Earth Asteroids
Qicheng Zhang, *University of California, Santa Barbara;* Kevin J. Walsh, Carl Melis, Gary B. Hughes, Philip Lubin, *USA*

23 – Simulations of Defense Strategies for Bennu: Material Characterization and Impulse Delivery Eric Herbold, *Lawrence Livermore National Laboratory;* John Owen, Damian Swift, Paul Miller, *USA*

20 – Spacecraft for Hypervelocity Impact Research – An Overview of Capabilities, Constraints and the Challenges of Getting There
Jan Thimo Grundmann, *DLR German Aerospace Center Institute of Space Systems;* Bernd Dachwald, Christian D. Grimm, Ralph Kahle, Aaron Dexter Koch, Christian Krause, Caroline Lange, Dominik Quantius, Stephan Ulamec, *Germany*

59 – Asteroid Diversion Considerations Comparisons Diversion Techniques
Michael Owen, *Lawrence Livermore National Laboratory;* Paul Miller, Jared Rovny, Joe Wasem, Kirsten Howley, Eric Herbold, *USA*

Technical Session 1:

High-Velocity Penetration Mechanics and Target Response

(*denotes Poster Session)

71 – Concurrent Velocimetry and Flash X-ray Characterization of Impact and Penetration in an Armor Ceramic
Brian E. Schuster, Brady B. Aydelotte, R. Brian Leavy, Sikhanda Satapathy, Michael B. Zellner, *U.S. Army Research Laboratory, USA*

We present a methodology for concurrent Photon Doppler Velocimetry (PDV) and in-situ flash X-ray imaging during ballistic impact of metallic penetrators into monolithic armor grade ceramic targets. Tungsten heavy alloy long rod penetrators were launched from a smooth bore cannon into silicon carbide targets at velocities of 0.753 and 1.403 mm/μs. Penetrator lengths and penetration depths were measured as a function of time using an array of four 450 kV flash X-ray sources and digital film. A four channel PDV system coupled to a 16 GHz oscilloscope was used to measure the velocity history of the penetrator and at three positions on the back surface of the target. This experimental technique shows great promise for measurements of the dwell time, penetration velocity, and the time of final break-out from the back of the target.

47 – Simulation and Experiments of Hypervelocity Impact in Containers with Fluid and Granular Fillings
Pascal Matura, *Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institute;* Georg Heilig, Martin Lueck, Martin Sauer, *Germany*

This paper presents both experiments and associated numerical simulations of hypervelocity impacts (approx. 3000 m/s) of spherical aluminum projectiles onto hollow aluminum cylinders with either water or sand filling, which serve as representative filling substances for fluid and powdery materials, respectively. High-speed video technique is used to monitor the impact process. The paper mainly focuses on the following two subjects: (a) A direct comparison of failure and fracture of the container shell and the associated release of the filling depending on its type in both experiment and simulation. (b) With the above mentioned cases as reference examples, the applicability and efficiency of different numerical methods is investigated, such as Langrangian discretizations with Finite Element (FE)/Smoothed Particle Hydrodynamics (SPH) coupling, a coupled adaptive FE/SPH discretization and a coupled Euler/Lagrange method. The influence of the different simulation methods in terms of container failure representation and ejecta cloud properties is investigated and compared with the experimental results.

(continued on the next page)

49 – Kinetic Energy Required for Perforating Double Reinforced Concrete Targets: A Parametric Numerical Study Considering Impact Velocity and Penetrator Presented Area

Christopher S. Meyer, *U.S. Army Research Laboratory, USA*

The U. S. Army's interest in breaching double-reinforced concrete (DRC) walls has revealed a need to better understand the energy required to perforate DRC. In an effort to determine the minimum kinetic energy required for perforating a DRC target, a parametric numerical study was conducted at the U. S. Army Research Laboratory. As an initial step in the exploration of minimum kinetic energy required for perforating DRC targets, large scale, high-fidelity, three-dimensional numerical simulations were conducted using an Eulerian shock physics code and an empirical concrete constitutive model. The parametric study investigated right cylindrical steel rods with masses of 500-2000 g and length-to-diameter ratios (L/D) of 1-10 impacting with velocities ranging from 500-2000 m/s, and perforating rebar reinforced concrete targets at three different impact locations with impact orientations to target of either end-on or side-on. This paper describes the modeling methodology used to generate the data, and then uses this data to consider the kinetic energy of perforation of DRC for the described range of conditions. Finally, an empirical fit to the data is reported, which may be used to estimate the conditions necessary for perforation of a DRC target of given parameters.

73 – High-Velocity Impact of Encased Al/PTFE Projectiles on Structural Aluminum Armor

Brett Sorensen, *Army Research Laboratory, USA*

In support of the U.S. Army's science and advanced technology objective in hypervelocity penetration mechanics, the Army Research Laboratory has been studying the terminal ballistics of conventional and non-conventional high-velocity kinetic energy projectiles against urban, light-armor and heavy-armor targets. The purpose is to identify and analyze both mechanisms and concepts to effectively defeat a range of targets with inert payloads using the elevated impact velocities available from future delivery systems. To this end, a series of experiments has been performed launching low-aspect-ratio aluminum and steel cylindrical projectiles, aluminum conical projectiles, and encased reactive material projectiles, with nominal masses between 200 and 240-gm, striking finite aluminum armor at nominal velocities of 2100 m/s to observe crater and spall formation and to determine the damage capacity of the debris.

58 – Modeling Plastic Deformation of Steel Plates in Hypervelocity Impact Experiments

Brendan O'Toole, *University of Nevada-Las Vegas and National Security Technologies;* Mohamed Trabia, Robert Hixson, Shawoon K. Roy, Michael Pena, Steven Becker, Edward Daykin, Eric Machorro, Richard Jennings, Melissa Matthes, *USA*

Hypervelocity impact experiments were done with a two-stage light gas gun to study the plastic deformation of metallic plates. Cylindrical Lexan projectiles were fired at A36 steel target plates with a velocity range of 4.5-6.0 km/s. Experiments were designed to produce a front side impact crater and a permanent bulging deformation on the back surface of the target while preventing complete perforation. Free surface velocities from the back surface of target plate were acquired using the newly developed Multiplexed Photonic Doppler Velocimetry (MPDV) system. Two different computational techniques were developed to simulate this type of experiment: Lagrangian-based smooth particle hydrodynamics (SPH) in LS-DYNA and the Eulerian-based hydrocode CTH. Parameters for material models including equation of state, compressive strength, and spall model were selected to obtain highest fidelity numerical results to compare with experiment.

85 – Shaped Charge Jet Penetration of Alon® Ceramic Assessed by Proton Radiography and Computational Simulations

Michael Zellner, *U.S. Army Research Laboratory and Los Alamos National Laboratory;* Richard Becker, Dattatraya Dandekar, Richard Leavy, Parimal Patel, *PRad Team, USA*

This work describes the use of proton radiography and continuum simulations to investigate the mechanics of a copper jet penetrating unconfined ALON® transparent ceramic. Use of proton radiography enabled characterization of the jet and ceramic material at 21 time steps, in situ, throughout the penetration process. These radiographs provide time-evolution data pertaining to the material densities, cavity growth, and material failure. The data were compared to legacy analytical penetration models and to a simulation of the event computed using a continuum multi-physics code. These comparisons revealed additional insights into the penetration mechanics as well as strengths and weaknesses of the computational algorithms and material models used in the simulations.

4* – Development of a Small Shaped Charge Insensitive Munitions Threat Test

Ernest L. Baker, *U.S. Army Armament Research Development and Engineering Center;* Arthur Daniels, Stanley DeFisher, Nausheen Al-Shehab, Koon-Wing Ng, Brian E. Fuchs, Felix Cruz, *USA*

Rocket propelled grenade (RPG) shaped charge attack threats are of particular concern for Insensitive Munitions (IM) development. In response to these threats, the U.S. Project Engineering Office for Ammunition (PEO Ammo) worked with ARDEC to develop a highly reproducible and well characterized standardized 81mm shaped charge jet initiation test configuration. This test was adopted by the U.S. DoD for RPG threat testing as specified in MIL-STD-2105D and is completed as per STANAG 4526. Recent U.S. Insensitive Munitions shaped charge initiation attention has been focused on realistic smaller shaped charge threats. STANAG 4526 discusses standardized threats related to "Top Attack Bomblets" and SCJ with "Characteristics of 50mm Rockeye". As a representative shaped charge for smaller size threats than the RPG, the 50mm Rockeye munition has been commonly recommended for testing. However, recent testing of the 50mm Rockeye munitions has shown a large undesirable variability of jet tip characteristics. This large variability in jet tip characteristics would be consistent with a large variability in munitions response to the 50mm Rockeye jet attack. Additionally, it has become clear that this shaped charge does not represent a commonly observed threat. For this reason, an effort is currently underway to identify a dominant smaller shaped charge threat and to develop a surrogate small shaped charge threat test configuration that provides very reproducible jet characteristics. The result to date is that 40mm grenades have been identified as a dominant smaller shaped charge threat and a surrogate consistent in approach with previous efforts has been designed.

8* – Mesoscale Simulations of High-Velocity Impact on Plain-Weave and 3-D Weave S-2 Glass Targets

Alexander J. Carpenter, E*ngineering Dynamics Department, Southwest Research Institute;* Charles E. Anderson, Jr., Sidney Chocron, *USA*

Mesoscale models have been successfully used to simulate impact on fabrics and composites at ordnance velocities. There are many advantages of the mesoscale models: 1) individual components of the model (e.g. yarns) can be easily tested to check if they capture the important physics of the problem, 2) the components of the model often have simple material models (e.g. a yarn is often linear elastic up to failure), and 3) a multi-tier validation with material and ballistics tests at meso- and macroscale levels can be performed. The authors have successfully developed mesoscale models for a glass fiber reinforced composite (S-2 glass fiber with epoxy resin) that were validated by unconventional composite tests (e.g., torsion, out-of-plane delamination). In this paper the models are exercised at impact velocities ranging from 2 to 5 km/s. The original material models have simple constitutive laws (linear-elastic and elasto-plastic) that, in principle, have limited validity for hypervelocity impact. Therefore, modifications are made to better model the high-rate behavior of the epoxy resin matrix. The simulation results capture complicated damage mechanisms that might provide insight into future experimental data.

18* – A Model for Penetration Resistance in Brittle Materials Taking Into Account Strain Hardening of Solid Phase in Mescal-Zone Powder Material

Boris Galanov, *I.N. Frantsevich Institute for Problems in Materials Science NAS Ukraine;* Valeriy Kartuzov, Sergei Ivanov, *Ukraine*

A new analytical model is proposed for penetration resistance of brittle materials that takes into account strain hardening of solid phase of powder material in Mescal zone ahead of penetrator. The strengthening is taken into account by analogy with theories of deformation and compaction of powder materials with elastic-plastic solid phase. The model is an extension of the penetration resistance model proposed by authors earlier. Model performance is demonstrated by example calculation of penetration resistance for glass which at high pressures shows residual densification and increase of elastic modulus. Strain hardening of solid phase was shown to increase penetration resistance.

21* – Simulations Of Hypervelocity Impacts Into Graphite

David Hébert, *CEA CESTA;* Gabriel Seisson, Isabelle Bertron, Ludovic Hallo, Jean-Marc Chevalier, Christian Thessieux, Francois Guillet, Michel Boustie, Laurent Berthe, *France*

This paper presents numerical simulations of hypervelocity impacts of 0.5-mm steel spheres into graphite, for velocities ranging between 1100 and 4500 m/s. Experiments have evidenced a non-monotonic evolution of the projectile penetration depth, along with the trapping of the projectile below the crater surface. Using numerical simulations and simple constitutive relations, we show how our experimental results can be related to both materials mechanical properties. We take advantage of the succession of physical mechanisms to build a step by step procedure and identify thresholds of yield and spall strength that allow a first restitution of the experimental results. These threshold values for the steel projectile were found to be consistent with the literature. As regards the graphite target, the yield strength has also been identified, and we propose to model its dependence with pressure through a linear relation. Comparisons between experiments and simulations are presented and discussed. Despite some difference at the highest impact velocities, the overall trend is well reproduced, which suggests that our results could be used as a starting point for further studies with more complex models.

35* – Development of Equipment to Estimate Momentum Shift in NEO Orbit Change by a Spacecraft Impact

Shohei Kage, *Department of Mechanical and Control Engineering, Kyushu Institute of Technology;* Satoshi Uenishi, Masashi Tanka, Takao Koura, Yasuhiro Akahoshi, *Japan*

For assessing the NEO orbit change by spacecraft impact, it is necessary to clarify the momentum shift at the impact time. Momentum shift is various amounts depending on the material of projectile and target, their shapes, and impact velocity. Currently, we have to collect more impact data by performing a simulated impact test on the earth because we do not have enough data to discuss design of a spacecraft impactor. Generally speaking, momentum shift is described at (= about 1 ~ 10 in other institution's impact tests). We aim to get more efficient momentum shift by creating experimental conditions in which is larger than 10. In this study, we developed a test equipment of pendulum type for measuring, and performed impact tests after calibration of the pendulum equipment.

51* – Ballistic Performance Model of Crater Formation in Monolithic, Porous Thermal Protection Systems

Joshua Miller, *University of Texas at El Paso, Jacobs, NASA Johnson Space Center, Lockheed Martin;* Eric Christiansen, Bruce Davis, Kevin Deighton, *USA*

Monolithic, porous, thermal protection systems were used heavily on the Apollo command module, and they are currently being used on the next generation of US manned spacecraft, Orion. These systems insulate reentry critical components of a spacecraft against the intense thermal environments of atmospheric reentry. Additionally, these materials may be highly exposed to space environment hazards like solid particle impacts. This paper discusses impact studies up to 10 km/s on nominally 0.56 g/cm3 Avcoat ablator with phenolic flexible hexcore. An impact model that describes projectile dispersion in a monolithic material is described that provides excellent agreement with observations over a broad range of impact velocities, obliquities and projectile materials.

69* – Surface Wave Effects on the Ballistic Response of Brittle Materials

Sikhanda Satapathy, *TKC Global Contractor at Army Research Laboratory & Army Research Laboratory;* Jason McDonald, *USA*

Prior experimental studies [1-3] have shown substantial improvement in the ballistic performance of ceramics due to surface treatment with thin coatings; however, no correlation between layer properties and degree of improvement has been found and no mechanism has yet been identified. It is certainly true that the high strain rates present in a ballistic event will cause surface waves to form and it is plausible that the interaction of these waves with surface flaws may contribute significantly to cracking and failure. In the present work a computational framework is developed to study the role of surface waves in brittle materials. Extension of this framework to multi-layer systems should provide insight into whether or not the observed surface-treatment effect in ceramics can be attributed to surface wave suppression.

Technical Session 2:

Hypervelocity Phenomenology Studies

(*denotes Poster Session)

34 – Hypervelocity Pressure Fields Driven by Cylindrical Converging Shock Used for Accelerating Dense Metal Particles

Charles Jenkins, *Air Force Research Laboratory, Munitions Directorate;* Robert Ripley, Chris Cloney, *USA*

The Cylindrical Converging Shock Tube is a novel explosion technology used to drive a shock or detonation wave through a core material at high velocity. The system contains an inner core and outer explosive annulus separated with an inner metal liner. Axial detonation of the annular explosive transmits a centrally converging shock in the form of a Mach stem into the core. With a slight modification to a Cylindrical Converging Shock Tube, a super compression detonation shock tube can be created which can provide a reactive core velocity of over 10 km/s by overdriving the annular explosive. An internal core pressure of several hundred gigapascal (GPa) can be produced depending on the item's geometry and core material properties. The study first examines the pressure fields in an inert PMMA core and then repeats the simulation for a reactive multiphase material of HMX/Al-W to identify the dynamics of an inert particle laden core. This study uses a Eulerian-to–Lagrangian conversion method to describe the particle dynamics occurring within the core.

39 – Control of Shaped Charge Jets Through Non-uniform Confinement

Geremy Kleiser, *Air force Research Laboratory, Munitions Directorate;* David Lambert, *USA*

This paper presents both experiments and associated numerical simulations of hypervelocity impacts (approx. 3000 m/s) of spherical aluminum projectiles onto hollow aluminum cylinders with either water or sand filling, which serve as representative filling substances for fluid and powdery materials, respectively. High-speed video technique is used to monitor the impact process. The paper mainly focuses on the following two subjects: (a) A direct comparison of failure and fracture of the container shell and the associated release of the filling depending on its type in both experiment and simulation. (b) With the above mentioned cases as reference examples, the applicability and efficiency of different numerical methods is investigated, such as Langrangian discretizations with Finite Element (FE)/Smoothed Particle Hydrodynamics (SPH) coupling, a coupled adaptive FE/SPH discretization and a coupled Euler/Lagrange method. The influence of the different simulation methods in terms of container failure representation and ejecta cloud properties is investigated and compared with the experimental results.

54 – Hypervelocity Penetration into Soil

Nicholas Nechitailo, *Naval Surface Warfare Center, USA*

This paper is focused on the physics of hypervelocity soil penetration. The influence of the shape, material and structural integrity of various impactors on penetration depth was investigated in the range of speeds between 0.3 and 4.0 km/s. Deviation of impactors from their initial trajectory, melting, erosion and spall has also been studied. Initially, with the increase in impact speed, the penetration depth increased. At a certain critical speed, the impactors reached their maximum penetration depth. With further increases in the impact speed the penetration depth declined. We developed refined analytical solutions to compute the maximum penetration depth achievable by a given impactor as well as its penetration depth in the region above the critical speed. These solutions accounted for the impactor weight, its length-to-diameter ratio and water content in soil. The results of these analytical predictions were compared with experimental data. Unexpected and rather damaging physical phenomena, including a fireball and unusual signals recorded by electronics, were observed in experiments involving hypervelocity impact against wet soil.

79 – Emission Spectroscopy of Hypervelocity Impacts on Aluminum, Organic and High-Explosive Targets

Jimmy Verreault, *TNO;* James Day, Wouter Halswijk, Jason Loiseau, Justin Huneault, Andrew J. Higgins, Adam D. Devir, *The Netherlands, Canada and Israel*

Laboratory experiments of hypervelocity impacts on aluminum, nylon and high-explosive targets are presented. Spectral measurements of the impact flash are recorded, together with radiometric measurements to derive the temperature of the flash. Such experiments aim at demonstrating that the impact flash produced by a ballistic missile interception contains the spectral information required to identify the content of the intercepted missile. It is shown that the elements that are part of the aluminum projectile and/or aluminum target are successfully identified

from the obtained spectra. For the case of a nylon/aluminum target organic molecular emission lines characteristic of CN and C2 are also identified. The CN molecular band is also observed for the case of a high-explosive target, although the detection of organic elements from such targets is more difficult than for nylon targets. In most cases, the temperature of the impact flash measured using the radiometer is in the range 2500 – 4000 K, whereas a comparison between simulated and experimental spectra shows temperatures up to 9000 K. Hence a conclusive impact flash temperature could not be obtained.

80 – The Vaporization Threshold: Hypervelocity Impacts of Ice Grains Into a Titanium Cassini Spacecraft Instrument Chamber

James D. Walker, *Southwest Research Institute;*
Sidney Chocron, J. Hunter Waite, Timothy Brockwell, *USA*

The Cassini spacecraft, currently in orbit around Saturn, has an Ion and Neutral Mass Spectrometer (INMS) on board as part of the scientific payload. There have been some unexpected readings of the instrument in flybys of the moon Enceladus. In relative encounter velocity, these flybys range from 7 to 18 km/s, and it has been suggested that ice grain impacts in the instrument could have a velocity-dependent response that influences the materials that the instrument records. To explore the physics of the impacts, computations were performed with CTH. Small ice grains (1 micron across) were impacted into a titanium alloy at a range of speeds of interest. Results are that the formation of a titanium vapor plume begins at impact velocities of 16 km/s. The transition to the formation of vapor of target material is fairly sharp. We explore the transition to determine the influence of ice grain geometry on the vapor formation transition. Efforts have been made to quantify the titanium vapor and titanium solid and liquid ejecta at various impact speeds, as all of these may influence chemistry in the instrument's antechamber and thus affect what ions or molecules are seen by the INMS.

2* – Asymmetric Material Impact: Achieving Free Surfaces Velocities Nearly Double That of the Projectile

Tariq Aslam, *Los Alamos National Laboratory;*
Dana Dattelbaum, Richard Gustavsen,
Robert Scharff, Mark Byers, *USA*

Hypervelocity impact speeds are often limited by practical considerations in guns and explosive driven systems. In particular, for gas guns (both powder driven and light gas guns), there is the general trend that higher projectile speeds often come at the expense of smaller diameters, and thus less time for examining shock phenomena prior to two dimensional release waves affecting the observed quantities of interest. Similarly, explosive driven systems have their own set of limiting conditions due to limitations in explosive energy and size of devices required as engineering dimensions increase. The focus in this study is to present a methodology of obtaining free surface velocities well in excess of the projectile velocity. The key to this approach is in using a high impedance projectile that impacts a series of progressively lower impedance materials. The free surface velocity (if they were separated) of each of the progressively lower impedance materials would increase for each material. The theory behind this approach, as well as experimental results, is presented.

32* – Shuttle MMOD Impact Database

James Hyde, *Jacobs, Johnson Space Center;*
Eric Christiansen, Dana Lear, *USA*

The Shuttle Hypervelocity Impact Database documents damage features on each Orbiter from micrometeoroids (MM) and orbital debris (OD). Data is divided into tables for crew module windows, payload bay door radiators and thermal protection systems along with other miscellaneous regions. The database contains nearly 3000 records, with each providing impact feature dimensions, location on the vehicle and relevant mission information. Additional detail on the type and size of particle that produced the damage site is provided when sampling data and definitive spectroscopic analysis results are available. Relationships assumed when converting from observed feature sizes in different shuttle materials to particle sizes will be presented.

61* – Holes Formed in Thin Aluminum Sheets by Spheres with Impact Velocities Ranging from 2 to 10 Km/S

Andrew Piekutowski, *University of Dayton Research Institute;* Kevin Poormon, *USA*

The dimensions of 96 holes produced by the impact of 2017-T4 aluminum spheres with various thicknesses of 6061-T6 aluminum sheets are presented and analyzed. The sphere diameters ranged from 1.40 mm to 19.05 mm and the sheet-thickness-to-projectile-diameter ratio, t/D, ranged from 0.008 to 0.618 with the majority of the tests having t/D ratios of less than 0.234. Impact velocities ranged from 1.98 km/s to 9.89 km/s. The measured hole diameters were normalized by dividing them by the diameter of the sphere that produced the hole. The normalized diameters of the holes are shown to scale when compared on the basis of t/D ratio. When the impact velocity was held constant, a relationship between the t/D ratio and the morphology of the lip structure surrounding the hole was noted. As the t/D ratio increased, the holes tended to be less circular and the lip morphology became more complex. The results of the analysis of all hole data was used to develop a description of the hole-formation sequence.

84* – Ultra-High-Speed Photography and Optical Flash Measurement of Nylon Sphere Impact Phenomena

Masahisa Yanagisawa, *University Electro-Communications;* Kosuke Kurosawa,
Sunao Hasegawa, *Japan*

An optical spike is sometimes observed prior to the main flash in high-velocity impact experiments. The spikes are particularly noticeable in the case of Nylon66 projectiles. In this study, we conducted experiments in which Nylon66 spheres impacted the flat surfaces of Nylon66 blocks perpendicularly at 7 km s-1. We observed the impact phenomena by using an ultra-high-speed camera and high-temporal-resolution photometers to identify the cause of the spikes. High-speed photographs show that the entire projectile was shining while it was penetrating a target. Glaring light from the shock front propagating in the projectile is assumed to become diffused within the translucent projectile and then radiated from its surface. The blackbody radiation from the shock front at 3600 K, which is calculated based on a one-dimensional shock model, accounts for the radiative intensities measured by the photometers. A sub-spike was observed just after the main spike in all the experiments conducted, the cause of which was not ascertained.

Technical Session 3:

Material Response

(*denotes Poster Session)

45 – Simulation-Based Study of Layered Aluminum Crystal Microstructures Subjected to Shock Loading

Jeffrey Lloyd, *Impact Physics, RDRL-WMP-C, US Army Research Laboratory, Aberdeen Proving Ground;* John Clayton, *USA*

A one-dimensional finite difference method allowing for anisotropic deformation is used in conjunction with a nonlinear thermoelastic-viscoplastic material model to compute the shock response of various microstructural instantiations of pure aluminum at peak stresses exceeding the Hugoniot Elastic Limit (HEL). Single crystals and layered bi-materials consisting of grains with alternating orientations relative to the direction of shock propagation -- specifically [100], [111], or low-symmetry orientations -- are impacted to peak shock stresses on the order of 5 GPa. The [111] orientation [111] is observed to be stiffest both plastically and elastically, while the [100] orientation is found to be most compliant. Layered bi-materials that only demonstrate pure longitudinal waves exhibit average shock stresses, entropy production, and internal energy in between values computed for their single crystal constituents. Layered bi-materials that generate both quasi-longitudinal and quasi-transverse waves results in lower peak stresses and higher internal energy than their single crystal constituents. In bi-material systems, stress fluctuations decrease in frequency with increasing layer thickness, and peak stress amplitudes increase with layer thickness. Average dissipation depends on orientation but is relatively insensitive to layer thickness. Results of the computational method may ultimately be used to guide design of metallic systems with microstructures tailored for optimal impact resistance.

66 – Shock Wave Structure in Particulate Composites

Michael Rauls, *California Institute of Technology;*
Guruswami Ravichandran, *USA*

An experimental study of shock wave profiles in particulate composites of various compositions is undertaken to determine how shock width and rise times depend on the mean particulate size. The composites under examination serve as a model for concrete or polymer bonded explosives, based upon the impedance mismatch between the relatively stiff particulates and compliant matrix. Polymethyl Methacrylate (PMMA) and glass spheres ranging in size from 100μm to 1000μm are used in concentrations of 30% and 40% glass by volume for experiments with a single bead size, and up to 50% glass by volume for multi-mode particle size distributions. A linear change in shock wave rise time is observed as a function of mean particulate diameter.

19 – The Unifying Role of Dissipative Action in the Dynamic Failure of Solids

Dennis Grady, *Applied Research Associates, USA*

Dissipative action, the product of dissipation energy and transport time, is fundamental to the dynamic failure of solids. Invariance of the dissipative action underlies the fourth-power nature of structured shock waves observed in selected solid metals and compounds. Dynamic failure through shock compaction, tensile spall and adiabatic shear are also governed by a constancy of the dissipative action. This commonality underlying the various modes of dynamic failure is described and leads to deeper insights into failure of solids in the intense shock wave event. These insights in turn are leading to a better understanding of the shock deformation processes underlying the fourth-power law. Experimental result and material models encompassing the dynamic failure of solids are explored for the purpose of demonstrating commonalities leading to invariance of the dissipation action. Calculations are extended to aluminum and uranium metals with the intent of predicting micro-scale energetics and spatial scales in the structured shock wave.

16 – Impact Compaction of a Granular Material

Gregg Fenton, *Applied Research Associates;*
Blaine Asay, Devon Dalton, *USA*

The dynamic behavior of granular materials has importance to a variety of engineering applications. Structural seismic coupling, planetary science, and earth penetration mechanics, are just a few of the application areas. Although the mechanical behavior of granular materials of various types have been studied extensively for several decades, the dynamic behavior of such materials remains poorly understood. High-quality experimental data are needed to improve our general understanding of granular material compaction physics. This paper will describe how an instrumented plunger impact system can be used to measure pressure-density relationships for model materials at high and controlled strain rates and subsequently used for computational modeling.

7 – Guided Impact Mitigation in 2D and 3D Granular Crystals

Hayden Burgoyne, *Caltech;* John Newman,
Wade Jackson, Chiara Daraio, *USA*

We simulate the dynamics of impacts on 1D, 2D and 3D arrays of metallic spheres in order to design novel granular protection systems. The dynamics of these highly organized systems of spheres, commonly called granular crystals, are governed by the contact law that describes how each particle interacts with the others. We use our recently developed force-displacement model of the dynamic compression of elastic-plastic spheres as the building block to investigate the response of systems comprised of metallic spheres to an impact. We first provide preliminary experimental results using a drop tower as validation of our numerical approach for 2D and 3D systems. We then use simulations of large periodic granular crystals in order to determine which particle properties govern the velocity of stress waves in these materials. We show that the properties of 1D systems can be scaled to predict the behavior of more complex 2D and 3D granular crystals. Because we can choose the material properties of each of the constituent particles and design how the particles are geometrically packed, we can leverage the heterogeneity of the system to create materials with unique properties such as anisotropic local stiffnesses and wave propagation velocities. We show that these materials allow us to design the dispersion and dissipation properties within the material in order to influence the propagation of a stress wave. Using these materials, we can therefore design protection systems or armor that directs damage away from sensitive parts or localizes damage to an unimportant area after impact from a projectile or a blast.

31 – Strength of Granular Materials in Transient and Steady State Rapid Shear

Ryan Hurley, *California Institute of Technology;*
Dana Dattelbaum, José Andrade, *USA*

This paper discusses relationships between the frictional strength of a flowing granular material and quantities including porosity and grain-scale energy dissipation. The goal of the paper is to foster an understanding of frictional strength that will facilitate the development of constitutive laws incorporating important physical processes. This is accomplished in several steps. First, a friction relationship is derived for a steady state simple shear flow using an energy balance approach. The relationship shows that friction is explicitly related to porosity, grain connectivity, and grain-scale dissipation rates. Next, the friction relationship is extended to describe transient changes in frictional behavior. The relationship shows that, in addition to the processes important for steady flows, the rate of dilatation and changes in internal energy play a role in the frictional strength of a granular material away from steady state. Finally, numerical simulations are performed to illustrate the accuracy of the friction relationships and illuminate important scaling behavior. The discussion of numerical simulations focuses on the rate-dependence of frictional strength and the partition of macroscopic energy dissipation into its grain-scale components. New interpretations of existing constitutive laws and ideas for new constitutive laws are discussed.

14* – Mesoscale Modeling of Quartzite and Sandstone under Shock Loading: Influence of Porosity and Pressure-Dependent Quartz Stiffness on Macroscopic Behavior

Nathanaël Durr, Fraunhofer EMI*;* Martin Sauer,
Germany

In this paper, quartzite and sandstone are numerically investigated under planar shock loading. Those geologic materials consist of cemented quartz grains. Quartzite has a compact structure whereas sandstone has a porosity of typically around 20 %. A mesoscale (grain scale) model is developed in order to catch inter-granular interactions and porosity crushing under shock loading. For this purpose, quartz grains are explicitly resolved in a Finite-Element model such that their shape and orientation are represented. The quartz grains are modeled as elastic crystals with a pressure-dependent, anisotropic stiffness matrix. Using parameter variations, we study the effect of porosity and pressure-dependency of the quartz stiffness on the macroscopic behavior of quartzite and sandstone. Descriptors of the macroscopic behavior are macroscopic longitudinal stress and shock wave speed. These quantities are determined via a homogenization methodology.

Technical Session 4:

Spacecraft Meteoroid/ Debris Shielding and Failure Analyses I

(*denotes Poster Session)

10 – Toughened Thermal Blanket for Micrometeoroid and Orbital Debris Protection

Eric Christiansen, *NASA Johnson Space Center;*
Dana Lear, *USA*

Toughened thermal blankets have been developed that greatly improve protection from hypervelocity micrometeoroid and orbital debris (MMOD) impacts. Three types of materials were added to the thermal blanket to enhance its MMOD performance: (1) disrupter layers, near the outside of the blanket to improve breakup of the projectile, (2) standoff layers, in the middle of the blanket to provide an area or gap that the broken-up projectile can expand, and (3) stopper layers, near the back of the blanket where the projectile debris is captured and stopped. Hypervelocity impact tests were performed on candidate toughened thermal blanket configurations at the NASA White Sands Test Facility and at the University of Dayton Research Institute. From these tests the best disrupter materials were found to be beta-cloth and fiberglass fabric. Polyimide open-cell foams provide a light-weight means to increase the blanket thickness and improve MMOD protection. The best stopper material is Spectra™ 1000-952 or Kevlar™ KM2-705. These blankets can be outfitted if so desired with a reliable means to determine the location, depth and extent of MMOD impact damage by incorporating an impact sensitive piezoelectric film.

13 – MMOD Puncture Resistance of EVA Suits with Shear Thickening Fluid (STF) – Armor™ Absorber Layers

Colin Cwalina, *Department of Chemical and Biomolecular Engineering, University of Delaware;*
Richard Dombrowski, Charles McCutcheon,
Eric Christiansen, Norman J. Wagner, *USA*

Absorber layers comprised of shear thickening fluid (STF) intercalated Kevlar® (STF-ArmorTM) are integrated within the standard extra-vehicular activity (EVA) suit and tested for efficacy against both needle puncture and hypervelocity impact (HVI) tests characteristic of micrometeoroids and orbital debris (MMOD). An improvement in puncture resistance against hypodermic needle threats is achieved by substituting STF-ArmorTM in place of neoprene-coated nylon as the absorber layer in the standard EVA suit. The prototype lay-ups containing STF-ArmorTM have the benefit of being 17% thinner and 13% lighter than the standard EVA suit and the ballistic limit is identified in HVI testing. The results here demonstrate that EVA suit lay-ups containing STF-ArmorTM as absorber layers offer meaningful resistance to MMOD threats.

48 – Numerical Investigations of Hypervelocity Impacts on Pressurized Aluminum-Composite Vessels

Jérome Mespoulet, *Thiot Ingenierie;* Fabien Plassard, Pierre-Louis Héreil, Patrick Thiot, *France*

Response of pressurized composite-Al vessels to hypervelocity impact of aluminum spheres have been numerically investigated to evaluate the influence of initial pressure on the vulnerability of these vessels. Investigated tanks are carbon-fiber overwrapped pre stressed Al vessels. Explored internal air pressure ranges from 1 bar to 300 bar and impact velocity are around 4400 m/s. Data obtained from experiments (Xray radiographies, particle velocity measurement and post-mortem vessels) have been compared to numerical results given from LS-DYNA ALE-Lagrange-SPH full coupling models. Simulations exhibit an under estimation in term of debris cloud evolution and shock wave propagation in pressurized air but main modes of damage/rupture on the vessels given by simulations are coherent with post-mortem recovered vessels from experiments. First results of this numerical work are promising and further simulation investigations with additional experimental data will be done to increase the reliability of the simulation model. The final aim of this crossed work is to numerically explore a wide range of impact conditions (impact angle, projectile weight, impact velocity, initial pressure) that cannot be explore experimentally. Those whole results will define a rule of thumbs for the definition of a vulnerability analytical model for a given pressurized vessel.

72 – Effects of Debris Cloud Interaction with Satellites Critical Equipments - Experiments and Modeling

Jean-Marc Sibeaud, *CEA DAM, GRAMAT;* Christian Puillet, *France*

The level of damage imparted on three types of satellites components resulting from hypervelocity impacts of aluminum projectiles onto a neighboring structural part have been assessed experimentally by using a double stage light gas gun. The experimental configurations were designed to simulate debris encounters with a space vehicle during its operational life time around the Earth. The first test was conducted against a set of separate harness strapped down on the inner surface of a carbon facesheet sandwich panel in order to assess the effectiveness of redundant cables spacing in case of unitary debris perforating impact onto the structure. The resistance to damaging of a silicon carbide mirror and a solar panel was then evaluated against debris cloud generated by prior impact of chunky debris with the satellite structure. Potential losses of electrical functional capabilities were then derived. The vulnerability/Survivability Pléiades software was updated accordingly.

24 – Hypervelocity Impact of Aluminum Projectiles Against Pressurized Aluminum-Composite Vessel

Pierre-Louis Héreil, *Thiot Ingenierie;* Jérome Mespoulet, Fabien Plassard, *France*

Vulnerability of high pressure vessels subjected to high velocity impact of space debris is analyzed with the response of pressurized vessels to hypervelocity impact of aluminum sphere. Investigated tanks are CFRP (carbon fiber reinforced plastics) overwrapped Al vessels. Explored internal pressure of nitrogen ranges from 1 bar to 300 bar and impact velocity are around 4400 m/s. Data obtained from Xrays radiographies and particle velocity measurements show the evolution of debris cloud and shock wave propagation in pressurized nitrogen. Observation of recovered vessels leads to the damage pattern and to its evolution as a function of the internal pressure. It is shown that the rupture mode is not a bursting mode but rather a catastrophic damage of the external carbon composite part of the vessel.

38* – Protective Performance of Hybrid Metal Foams as MMOD Shields

Andreas Klavzar, *French-German Research Institute of Saint-Louis (ISL);* Maxime Chiroli, Anne Jung, Bernhard Reck, *France and Germany*

Open cell aluminum foam core sandwich panel structures have been proven to be of interest for protecting satellites against micrometeoroids and orbital debris (MMOD). Bumpers containing aluminum foam show outstanding capabilities to induce multiple shocks to small projectiles in the hypervelocity regime. For this work the protective performance of foam cored sandwich panels with cores made from newly developed hybrid metal foams was evaluated. Therefore shots in the hypervelocity regime on the two-stage light gas gun of the French-German Research Institute of Saint-Louis were performed. The tested targets were sandwich panels with aluminum front and rear facesheets and cores of different types of metallic foams: foams with pore densities of 10 pores per inch and 45 pores per inch were tested as pure aluminum and hybrid metallic foams. The projectiles to simulate micrometeoroids and orbital debris were aluminum spheres with a diameter of 4mm. The impact velocity was 6500m/s. It could be shown experimentally that the nickel coating of the aluminum foams leads to a decreased crater depth in the sandwich panels. However, scatter in the coating thickness leads to variations in the foam densities of the hybrid foams, making the evaluation of the increase in the protective performance difficult. Nevertheless, due to the nickel coating the influence of the pore density seems to be more significant than reported before. By reducing the coating thickness and using high performance aluminum alloys as base material for the hybrid foams, further optimization of the protective performance could be reached. Then, the complete evaluation of the ballistic limit over a broad velocity regime should be done to see the variations in the performance of the hybrid foams over the whole velocity range being of interest for MMOD shielding technologies.

43* – Impact Frequency Estimate of Micron-sized Meteoroids and Debris on Tanpopo Capture Panels on the ISS

Manami Kurihara, *Hosei University;* Masumi Higashide, Yuu Takayanagi, Kazuyoshi Arai, Hajime Yano, Makoto Tabata, Sunao Hasegawa, Akihiko Yamagishi, *Japan*

This study is a part of 'Tanpopo' mission, which is to be mounted on the Exposure Facility of the Japanese "Kibo" Module of the International Space Station. The purpose of this study is to comparing the impact frequency that is predicted from the debris environment model and the impact craters on the exposed instrument. There are two approaches to achieve this plan. The first is to predict the impact frequency of the micron-sized debris onto the Tanpopo capture panels which is exposed to space. The second is to establish methods for calculating key parameters in relation to impacting debris particles from excavated craters on the capture panel material. The debris impact frequency on the capture panels was predicted using the impact-risk analysis tool. It was found that impact of particles of 10μm or less in diameter was expected on the panels. Additionally, the relationship between the debris impact energy and crater was also derived by hypervelocity impact experiments. It was found that regardless of the projectile materials and impact speed, the relationship between the impact energy and the crater volume is nearly proportional.

53* – HVI Ballistic Limit Characterization of Fused Silica Thermal Panes

Joshua Miller, *University of Texas at El Paso and NASA Johnson Space Center;* William Bohl, Eric Christiansen, Bruce Davis, Kevin Deighton, *USA*

The dimensions of 96 holes produced by the impact of 2017-T4 aluminum spheres with various thicknesses of 6061-T6 aluminum sheets are presented and analyzed. The sphere diameters ranged from 1.40 mm to 19.05 mm and the sheet-thickness-to-projectile-diameter ratio, t/D, ranged from 0.008 to 0.618 with the majority of the tests having t/D ratios of less than 0.234. Impact velocities ranged from 1.98 km/s to 9.89 km/s. The measured hole diameters were normalized by dividing them by the diameter of the sphere that produced the hole. The normalized diameters of the holes are shown to scale when compared on the basis of t/D ratio. When the impact velocity was held constant, a relationship between the t/D ratio and the morphology of the lip structure surrounding the hole was noted. As the t/D ratio increased, the holes tended to be less circular and the lip morphology became more complex. The results of the analysis of all hole data was used to develop a description of the hole-formation sequence.

82* – Preliminary Study on Wood Stuffed Shield Configuration

Xue-zhong Wen, *Hypervelocity Aerodynamics Institute, China Aerodynamics Research and Development Center;* Yi Li, Jie Huang, Ping Chen, Yao Long, Sen Liu, *China*

As an effort to find a lighter shield, the wood stuffed shield was proposed in this paper based on the wood properties such as low density, low cost, high yield strength when the strain rate is high. Hypervelocity impact tests (Φ5.5mmΦV=4.79km/s~4.96km/s) were carried out to compare the shielding capabilities of the pinewood stuffed shield, aluminum triple-wall shield and Nextel/Kevlar fabric stuffed shield with the same areal density. It was found in all the tests that a perforation with diameter of 2.0mm was formed in the rear plate of the aluminum triple-wall shield. No perforation but slight deformation was found in the rear plates of both pinewood stuffed shield and Nextel /Kevlar fabric stuffed shield. The height of the deformation on the rear plates of the pinewood stuffed shield was 1.99mmm, and that on the Nextel/Kevlar fabric stuffed shield was 2.01mm. Results show that, with the same areal density, the shielding capability of the wood stuffed shield is greater than that of the aluminum triple-wall shield and is similar to that of Nextel /Kevlar fabric stuffed shield which is widely used on the spacecraft. To explore the reason why the shielding capability of the wood stuffed shield is prominent, the SPH (smoothed particle hydrodynamic) simulation on the glass-epoxy stuffed shield was carried out.

83* – Orbital Debris Wire Harness Failure Assessment for the Joint Polar Satellite System

Joel Williamsen, *Institute for Defense Analyses;* Kosuke Kurosawa, Steven Evans, *USA*

The objective of this paper is to present the results of two hypervelocity impact failure risk assessments for critical wire bundles exposed aboard the Joint Polar Satellite System (JPSS-1) to an increased orbital debris environment at its 824 km, 98.8 deg inclination orbit. The first "generic" approach predicted the number of wires broken by orbital debris ejecta emerging from normal impact with multi-layer insulation (MLI) covering 36, 18, and 6 strand wire bundles at a 5 cm standoff using the Smooth Particle Hydrodynamic (SPH) code. This approach also included a mathematical approach for computing the probability that redundant wires were severed within the bundle. Based in part on the high computed risk of a critical wire bundle failure from the generic approach, an enhanced orbital debris protection design was examined, consisting of betacloth-reinforced MLI suspended at a 5 cm standoff over a seven layer betacloth and Kevlar blanket, draped over the exposed wire bundles. A second SPH-based risk assessment was conducted that also included the beneficial effects from the high (75 degree) obliquity of orbital debris impact and shadowing by other spacecraft components, and resulted in a considerably reduced likelihood of critical wire bundle failure compared to the original baseline design.

Technical Session 5:

Fracture and Fragmentation

(*denotes Poster Session)

5 – The Mechanochemistry of Damage and Terminal Ballistics

Todd Bjerke, *US Army Research Laboratory, Aberdeen Proving Ground;* Michael Greenfield, Steven Segletes, *USA*

The asymmetric radial crack patterns that occur in brittle targets when impacted by high velocity projectiles are explained using a Phenomenological Mechanochemistry of Damage (PMD) engineering model. The developed model, which constitutes a simplification of the generalized PMD framework, reveals an energy instability during failure of brittle materials configured in a purely symmetric geometry and impact configuration. The underlying cause of the instability is due to the competition between stored elastic energy and the energy associated with new surface creation through broken chemical bonds. The instability manifests itself in the form of asymmetric radial cracking in the brittle target. The model is built upon the general PMD framework and assumes the target material is sufficiently brittle that strains are small and linear elasticity is applicable. Furthermore, the impact geometry is assumed to be purely symmetric, which leads to a reduction of the geometry to a one-dimensional radial configuration. The model is not restricted to any ballistic impact speed regime, provided the target material remains in the solid phase.

37 – Stress Wave and Damage Propagation in Transparent Materials Subjected to Hypervelocity Impact

Nobuaki Kawai, *Kumamoto University;* Syunske Zama, Wataru Takemoto, Kairi Moriguchi, Kazuyoshi Arai, Sunao Hasegawa, Eiichi Sato, *Japan*

Hypervelocity impact experiments have been conducted on transparent materials, SiO2 glass and polycarbonate, to observe directly the impact-induced damage process progressing inside materials. Stress wave propagation and damage evolution associated with hypervelocity impact are visualized by employing the Edge-on Impact technique coupled with an ultra-high-speed video camera. Recorded images clearly show how stress wave propagate and interact each other, and how damages form and propagate during hypervelocity-impact event. In the impacted SiO2 glass, the damages on the ballistic direction are formed associated with the propagation of a shear wave. And, the interaction of the shear wave with the longitudinal wave reflected from free surface initiates the drastic nucleation of damage points. In the impacted polycarbonate, in addition to penetration damage and spall fracture, the delamination-like fracture is initiated by the interaction of the reflected rarefaction waves from both side free surfaces. However, such delamination fracture does not extended inside the plastic deformed region induced by the penetration of the impacted projectile.

41 – Incorporation of Material Variability in the Johnson Cook Model

Ryan Kupchella, *Corvid Technologies;* David Stowe, Xudong Xiao, Anne Algoso, John Cogar, *USA*

The Johnson Cook (JC) material model is often used for modeling hypervelocity impacts (HVI) because it is capable of capturing high rate deformation and temperature effects. Within the JC model, material damage leading to fracture is aggregated using a path dependent damage parameter. Contributions to the damage parameter are calculated at each cycle as the quotient of incremental effective plastic strain over the effective failure strain. The effective failure strain is a function of the stress state, strain rate, and temperature which changes locally throughout the simulation. Solid bodies often demonstrate variability in resilience resulting from material inclusions and defects. Therefore, in addition to the deterministic, state-based variability in the effective failure strain inherent to the JC model, efforts are often made to capture the effect of general material non-uniformity. Although other approaches may be available, the Weibull probability distribution is often employed within failure analyses to allow simulations to diverge from a completely uniform solution. In this paper, we investigate several methods of augmenting the JC damage model with Weibull variability. The implementation of each method provides a means for measured material uncertainty to enter the calculation. We focus on a standard three-parameter Weibull probability density function (pdf) although the methods proposed can be used with any probability distribution. Characteristics of the pdf are preserved within a solid body at its initial state but differ in the effect the JC effective failure strain has on these characteristics as the material state changes. The Weibull pdf under various loading conditions is discussed, and simulation results incorporating these methods are compared with those employing only the JC damage model or Weibull variability.

56 – Ejecta Cone Angle and Ejecta Size Following a Non-Perforating Hypervelocity Impact

Masahiro Nishida, *Nagoya Institute of Technology;* Yasuyuki Hiraiwa, Koichi Hayashi, Sunao Hasegawa, *Japan*

The effects of projectile diameter and impact velocity on ejecta cone angle and ejecta size distribution were investigated by striking aluminum alloy 6061-T6 targets with aluminum alloy 2017-T4 spheres at velocities ranging from 2 to 6 km/s. The two-stage light-gas gun at the Institute of Space and Astronautical Science (ISAS)/ Japan Aerospace Exploration Agency (JAXA), and Nagoya Institute of Technology was used for the experiments. To examine the scattering angles of ejecta, a witness plate (150 mm × 150 mm, 2 mm in thickness) made of copper C1100P-1/4H, with a 30-mm hole in the center, was placed 50 mm in front of the target.

78 – A Quantitative Approach to Comparing High Velocity Impact Experiments and Simulations Using XCT Data

Andrew Tonge, *The Johns Hopkins University;* Brian Leavy, Jerry LaSalvia, K.T. Ramesh, Rebecca Brannon, *USA*

While computational models of impact events have the potential to accelerate the design cycle, one's confidence in a material model should be related to the extent of validation work that has been performed for that model. Quantities of interest used for validation are often either scalar volume-averaged quantities (such as the average density, or the force applied to a boundary) or field quantities (such as the strain field obtained from digital image correlation, or density maps computed from X-ray computed tomography (XCT)). Volume averaged quantities are easy to compare quantitatively since they are either a single value or a simple time series. However, these averaged quantities do not capture differences in the failure process within a material and can be blunt instruments for validation efforts. Field quantities provide spatial information, but are difficult to reduce to a scalar that quantifies the goodness of a particular model with respect to another model. This work describes an approach to using XCT data to quantify how well a particular simulation agrees with simulation data while accounting for the statistical nature of failure in brittle materials.

1* – Tunable Charge with Internal Layers

Werner Arnold, *MBDA – TDW, Germany*

Increasingly asymmetric conflicts within urban terrains are requiring not only a high precision weapon system but also a munition with large flexibility in performance. Today's warheads don't have these capabilities resulting in a significantly reduced freedom of action. During the last decade TDW put a lot of effort into the research of new warhead technologies trying to change this inappropriate situation. In previous papers the very first ideas meeting these challenges were presented. In the meantime further progress was achieved leading to new warhead concepts. A radially Switchable Modes Warhead (SMW) and a Scalable Effects Warhead (SEW) were discussed. Finally two other concepts now on axially Switchable Modes

Warheads were presented (see also references). In the current paper an idea on radially performing warheads already shortly discussed in a previous work was resumed and will be further pursued in this work. An internal layer was used in this study to influence the performance of the fragmenting casing thus making the warhead tunable.

17* – Revision Plan of ISO11227 Considering Oblique Impact Tests

Yosuke Fujimura, *Kyushu Institute of Technology;* Yasuhiro Akahoshi, Takao Koura, Pauline Faure, Koichi Norimatsu, Yassine Serbouti, *Japan*

The number of space debris is continuously increasing, and the risk of collision with a spacecraft is also increasing Secondary debris called ejecta is specifically threat to spacecraft, so an international standardization of the test procedure to evaluate ejecta, was developed and published as ISO11227 on September 15, 2012. This paper intends to show the necessity of oblique impact test by comparing spacecraft material oblique impact with normal impact and to consider the experimental condition of oblique impact test to revise this standard.

28* – Applicability of Statistical Flaw Distributions of Eglin Steel for Fracture Calculations

Michael Hopson, *Naval Surface Warfare Center Dahlgren Division;* Christine Scott, David Lambert, *USA*

Computational continuum codes can provide many details on the response of metals to high velocity impact and explosive loading events. However, most "production" level calculations use a homogeneous description of the metal. This is an incorrect representation since metals possess a microstructure whose details create variations in material strength and other properties such as strain to failure. Ultimately these variations influence the formation of fragments at the macroscopic level. The spatial scale of the microstructure is on the order of micrometers and is not readily accessible to current computational tools and resources for system level calculations. Rather than explicitly model the microstructure one can attempt to capture the effects of material non-homogeneity through the use of a statistical description. Specifically, a statistically compensated failure strain criterion can be used to simulate the non-homogeneity of a material. This technique has been used previously by the authors on a tungsten alloy with some success. In those experiments, tungsten alloy rings were subjected to explosive loading. This resulted in a stress state approaching uniaxial stress. Furthermore, the tungsten alloy had relatively low ductility. The combination of these two factors resulted in fragments that were formed by tensile failure. It is important to determine if this technique can be used on a more ductile material under a different stress state. Fragmentation data was available for explosively loaded cylinders of Eglin Steel-1 (ES-1). The combination of the cylinder geometry and a more ductile metal resulted in fragments formed by shear failure. The experiment was simulated using CTH for the explosive and Pronto3D for the ES-1. Comparisons of the cylinder calculation results are made to the experimental fragmentation data and the results analyzed show a viable path forward on the use of statistical descriptions of these continuum models.

Technical Session 6:

Armor/Anti-Armor and Ballistic Technology

(*denotes Poster Session)

3 – Impact and Penetration of SiC: The Role of Rod Strength in the Transition from Dwell to Penetration

Brady Aydelotte, *US Army Research Laboratory;* Brian Schuster, *USA*

The phenomenon of dwell during projectile impact on ceramics has been an active area of research for several decades. Dwell in confined ceramics has received much attention, particularly the role of cover plates and their influence over the dwell to penetration transition. Dwell during long rod impact on unconfined ceramics has received relatively less attention. The present work will compare and contrast the results of two series of long rod impacts on hot pressed silicon carbide targets. One series utilized gold wire rods. The other series utilized rods fabricated from tungsten carbide with 10% cobalt matrix. A novel ten-flash X-ray system captured spatially resolved images of the penetration events. The experimental results are compared with simulations and predictions from the Alekseevskii-Tate equation to explore the role of shock pressure, the effects of the strength of the rod material in dwell to penetration transition behavior, and the behavior of defects within silicon carbide.

77 – Method for Prediction of Fragment Impact Response Using Physics Based Modeling and Statistical Analysis

Justin Sweitzer, *CGI Federal;* Nicholas Peterson, *USA*

A method for determining the response of a munition to the Fragment Impact (FI) stimulus based on hydrocode modeling and statistical analysis is presented. A modified version of the Hugh James Criterion is coupled to a logistic regression technique to obtain a normalized distance from initiation threshold as determined experimentally through FI tests. The method has been shown to correlate well with observations at multiple impact velocities with various configurations of FI mitigation schemes. A total of 65 FI shots have been completed to date on the TOW 2B warhead through two different shotlines, and the data will be presented here. The two shotlines are through the cylindrical section and the boattail section of the warhead. When fit to the overall data set, 51 out of 65 observations are correctly categorized.

55 – Numerical Modelling of Ultra-High Molecular Weight Polyethylene Composite Under Impact Loading

Long Nguyen, *RMIT University;* Torsten Lässig, Shannon Ryan, Werner Riedel, Adrian Mouritz, Adrian Orifici, *Australia and Germany*

Numerical models are investigated and refined for analysis of ultra-high molecular weight polyethylene (UHMW-PE) composite under ballistic and hypervelocity impact. An existing non-linear orthotropic continuum model implemented in a commercial hydrocode (ANSYS® AUTODYN®) was evaluated using a previously published material data set. It was found that the material through-thickness shear performance was artificially degraded as a result of coupling to the through-thickness tensile properties, significantly affecting the model accuracy for impact velocities in the ballistic regime. In order to correct for this, the composite laminate was discretized into sub-laminates joined by bonded contacts breakable through a combined tensile and shear stress failure criterion. The sub-laminate method allows the through-thickness tension and shear failure to be decoupled in the bulk material. This method was investigated and validated against experimental ballistic and hypervelocity impact tests. Simulations showed improvement in ballistic limit predications for thin targets under low velocity impact. Prediction of target deflection is also significantly improved compared to the baseline model in terms back face deformation. Under hypervelocity impact, good agreement with the experimental ballistic limit and residual velocities is still maintained, with a small variation between the new and baseline models. A third validation case was performed to investigate the model performance with thicker targets (50 mm) for impact velocities between the two baseline studies. Accuracy for this condition is poor and remains a challenge for the numerical model.

60 – Composite Material Particle Impact Mitigation Sleeve Testing

Nicholas Peterson, *US Army AMRDEC;* Justin Sweitzer, *USA*

This paper will present the results from four series of Fragment Impact (FI) tests on the TOW 2B warhead utilizing multiple Particle Impact Mitigation Sleeve (PIMS) configurations. Previously it has been demonstrated that the addition of a plastic, typically ULTEM® 1000, PIMS reduces the sensitivity of a munition to the FI threat. The mechanism by which the sensitivity is reduced is the reflection of the shockwave at the interface between the PIMS and the munition case material. The munitions to which this protection scheme has been applied previously use PBXN-9 as the main fill explosive and are therefore easier to protect using a single component PIMS than TOW 2B, which uses LX-14 as the main fill. LX-14 is a more sensitive explosive than PBXN-9, and requires additional material in the shotline to reduce the shock pressure in the explosive via reduction of velocity, breakup of the incoming fragment, and shock reflection at the interface between the case and the PIMS. The test results demonstrate that TOW 2B can be protected using a plastic PIMS in combination with a second layer of hard material spaced from the munition to break the fragment and slow it down prior to impact with the PIMS.

44 – Investigations of High Performance Fiberglass Impact Using a Combustionless Two-Stage Light-Gas Gun

Leslie Lamberson, *Drexel University, USA*

Two types of high performance fiberglass panels were investigated at normal impact conditions of around 1 km/s (2200 mph). Thin phenolic laminates of plain-weave glass cloth impregnated with synthetic thermosetting resins, one melamine and the other epoxy, were impacted by a 1.6 mm diameter nylon sphere using a combustionless two-stage light-gas gun. The resulting impact and ejecta was captured using high-speed imaging, and the perforation characteristics and damage zone were examined post-mortem using optical microscopy. Both composites had a fiber volume fraction of an estimated 56% and identical fiber weave so that the role of the matrix on impact performance could be comparatively investigated. The epoxy fiberglass resulted in full perforation of the target, whereas the melamine fiberglass resulted in deformation, but not full perforation. The overall damage zone of melamine fiberglass was twice the size on the rear surface than the epoxy fiberglass. In addition, the melamine fiberglass rear damage zone was 5 times the impactor diameter and exhibited ductile debonding and delamination as the main failure mechanisms. In contrast, the epoxy matrix rear damage was 3 times the impactor diameter and exhibited brittle failure mechanisms of fiber breakage and pullout. These experimental results suggest that the matrix material is a driving factor in the impact damage and perforation characteristics, and is discussed in context of the compressive and tensile strength at break of the materials.

Technical Session 7:
Analytical and Numerical Methodologies
(*denotes Poster Session)

64 – Analysis of Impact Melt and Vapor Production in CTH for Planetary Applications

Stephanie Quintana, *Brown University;* David Crawford, Peter Schultz, *USA*

This paper explores impact melt and vapor generation for a variety of impact speeds and materials using the shock physics code CTH. The study first compares the results of two common methods of impact melt and vapor generation to demonstrate that both the peak pressure method and final temperature method are appropriate for high-speed impact models (speeds greater than 10 km/s). However, for low-speed impact models (speeds less than 10 km/s), only the final temperature method is consistent with laboratory analyses to yield melting and vaporization. Finally, a constitutive model for material strength is important for low-speed impacts because strength can cause an increase in melting and vaporization.

42 – SPH Modeling Improvements for Hypervelocity Impacts

Ryan Kupchella, *Corvid Technologies;* David Stowe, Mark Weiss, Hua Pan, John Cogar, *USA*

Smoothed Particle Hydrodynamics (SPH) are often used to model solid bodies undergoing large deformation during hypervelocity impacts due to the ability of the method to handle distortion without the mesh entanglement issues posed by other Lagrangian discretizations such as the finite element method. Rather than using mesh connectivity, SPH uses a kernel function and performs smoothed integration over nearest neighbors to enforce the conservation laws of continuum dynamics. A number of improvements to the formulation have been proposed to increase stability and accuracy of the results. Despite such improvements, the performance of the SPH method is limited by the way in which boundary conditions are applied. Deficiency in the SPH field near solid boundaries is a shortcoming inherent to the formulation resulting in an inaccurate representation of contact mechanics during an impact event. To address this, the first part of this work focuses on improving SPH contact by treating the particles as if they were nodes in a finite element mesh. We investigate the effect of distributing contact loads across free surfaces using a Lagrange multiplier scheme. In addition, we propose a method for improving the initial distribution of Lagrangian particle mass and evaluate its effective on pressure waves traveling through a body. There is also potential to improve SPH modeling during non-uniform deformation resulting from impact. As deformation occurs, compressive forces cause SPH particle density to increase in the impact direction and decrease perpendicular to the impact. This can reduce accuracy in the perpendicular plane as the spatial resolution is coarsened. In the most extreme cases, numerical fracture can occur when the particles disperse to the degree that immediate neighbors are no longer recognized. We demonstrate the use of an ellipsoid kernel method, allowing the kernel to deform anisotropically with the particle field to maintain resolution and prevent numerical fracture. We discuss the implications of the method with respect to hypervelocity impacts, and compare results with baseline output obtained using a typical spherical kernel to evaluate its effectiveness.

50 – Analytic Ballistic Performance Model of Whipple Shields

Joshua Miller, *University of Texas at El Paso and NASA Johnson Space Center;* Michael Bjorkman, Eric Christiansen, Shannon Ryan, *USA and Australia*

The dual-wall, Whipple shield is the shield of choice for lightweight, long-duration flight. The shield uses an initial sacrificial wall to initiate fragmentation and melt an impacting threat that expands over a void before hitting a subsequent shield wall of a critical component. The key parameters to this type of shield are the rear wall and its mass which stops the debris, as well as the minimum shock wave strength generated by the threat particle impact of the sacrificial wall and the amount of room that is available for expansion. Ensuring the shock wave strength is sufficiently high to achieve large scale fragmentation/melt of the threat particle enables the expansion of the threat and reduces the momentum flux of the debris on the rear wall. Three key factors in the shock wave strength achieved are the thickness of the sacrificial wall relative to the characteristic dimension of the impacting particle, the density and material cohesion contrast of the sacrificial wall relative to the threat particle and the impact speed. The mass of the rear wall and the sacrificial wall are desirable to minimize for launch costs making it important to have an understanding of the effects of density contrast and impact speed. An analytic model is developed here, to describe the influence of these three key factors. In addition this paper develops a description of a fourth key parameter related to fragmentation and its role in establishing the onset of projectile expansion.

76 – Improved Artificial Viscosity in Finite Element Method (FEM) for Hypervelocity Impact Calculations

David Stowe, *Corvid Technologies;* Ryan Kupchella, John Cogar, *USA*

In this paper we develop methods based primarily on the work of Kuropatenko and Wilkins to improve the application of artificial viscosity in 3D finite element method (FEM) codes. The primary goal is to obtain better shock predictions for hypervelocity impacts (HVI) and reduce the need for user calibration. We focus on examining factors such as geometric variability with respect to shock direction, dynamic adaptation to changes in compressibility in the shock front, and anisotropic compression in multi-dimensional formulations. We implement the methods in the Velodyne hydro-structural code and investigate the effects on shock propagation using a series of simple flyer impact test cases which cover a range of system responses including strong and weak shocks. Various initial mesh geometries are utilized to examine mesh effects. Energetic materials using the Ignition and Growth Reactive Burn (IGRB) equation of state (EOS) are also examined due to the rapid change in compressibility and energy density which occurs due to reaction. These rapid changes can lead to insufficient damping in artificial viscosity calculations and thus provide an effective test case. We employ the CTH hydrocode to evaluate baseline shock behavior. The regular, ordered mesh of CTH allows for a consistent and precise application of the artificial viscosity. Direct numerical comparisons are used rather than experimental data to eliminate uncertainty due to factors such as material characterizations, EOS models, and mesh resolution. We compare the CTH results against various FEM artificial viscosity implementations to evaluate performance. It is demonstrated that shock response in FEM codes can be significantly improved by using updated artificial viscosity methods.

67 – Support Vector Machines for Characterising Whipple Shield Performance

Shannon Ryan, *Defence Science and Technology Organisation;* Sewandi Kandanaarachchi, Kate Smith-Miles, *Australia and Singapore*

Support Vector Machines (SVMs) are a classification technique used in data mining and machine learning that are particularly well suited for application with sparse data sets. A database of over 1100 hypervelocity impact tests using spherical aluminium projectiles against spaced aluminium armour (i.e. Whipple shield) was compiled and used to train four different SVMs. The SVMs were developed using a variety of input-attributes and Principal Component Analysis (PCA). Initially, a maximum accuracy of 75% was obtained for an SVM when applied to predict the perforated/not-perforated outcome of impact events not included in the training process. A number of tests were identified which were inconsistent with the pattern observed for other training data. By removing this conflicting data (<5% of the total number of entries), significant increases in the training and generalization accuracy (83%) were achieved. The qualitative outputs of the SVMs were investigated through comparison with classical ballistic limit curves and test data. Within a velocity range of ~3-8 km/s the SVMs demonstrated a good level of agreement with the classical ballistic limit curves and test data. The application of machine learning methods, including SVM, to predict impact outcomes is limited by the statistical quality of the training dataset. A broader and more homogenous distribution of test conditions, target geometries, materials, and outcomes (i.e. from well above to well below the ballistic limit) is required for machine learning to provide a high level of quantitative accuracy with consistent qualitatively output. Improvements to the training data set may be best achieved via a process in which the current SVMs are applied to identify the most valuable test conditions for future analysis.

12 – Computational Modeling of Electrostatic Charge and Fields Produced by Hypervelocity Impact

David Crawford, *Sandia National Laboratories*, *USA*

Following prior experimental evidence of electrostatic charge separation, electric and magnetic fields produced by hypervelocity impact, we have developed a model of electrostatic charge separation based on plasma sheath theory and implemented it into the CTH shock physics code. Preliminary assessment of the model shows good qualitative and quantitative agreement between the model and prior experiments at least in the hypervelocity regime for the porous carbonate material tested. Moreover, the model agrees with the scaling analysis of experimental data performed in the prior work, suggesting that electric charge separation and the resulting electric and magnetic fields can be a substantial effect at larger scales, higher impact velocities, or both.

Technical Session 8:

High-Velocity Launchers and Diagnostics

(*denotes Poster Session)

29 – Benchmarking Surface Position from Laser Velocimetry with High-Speed Video in Impact Experiments

Marylesa Howard, *National Security Technologies;* Aaron Luttman, Eric Machorro, Rand Kelly, Jerome Blair, Melissa Matthes, Michael Pena, Michael Hanache, Brendan O'Toole, Nathan Sipe, Kristen Crawford, B. T. Meehan, Robert Hixson, *USA*

Photonic Doppler Velocimetry (PDV) is a heterodyne laser interferometric technique for computing the velocities of free surfaces moving up to tens of kilometers per second. This information can be used to infer material properties such as equation of state and phase transitions, many of which are unknown even for common materials like steel. Broadly speaking, the methods of computing velocity from the voltages measured on an oscilloscope are either local or global in time, either frequency-based or phase-based, and formulated either statistically or deterministically. It is important to understand how velocities extracted using the different classes of methods relate to each other and how the results relate to measurements from independent diagnostics. In this work we present computed surface velocities of a flat plate of stainless steel impacted by a projectile traveling approximately 4 km/s from a light gas gun, using several different extraction methods, and we benchmark the results of the different PDV analyses against high-speed video captured at 5 million frames per second with a hybrid framing-video camera. The different extraction methods all show the same large-scale structures in the computed velocity profiles–and they agree with the high-speed video at the appropriate time scale–but they each show different small-scale features. We discuss the nature of these features, including descriptions of the numerical artifacts that one would expect with each of the different analysis techniques applied. Descriptions of the methods are provided, with a focus on the Local Polynomial Approximation method, and its uncertainty quantification, developed by the authors.

46 – The Analysis Technique for Ejecta Cloud Temperature Based on Atomic Spectrum

Zhao-xia Ma, *CARDC;* Jie Huang, An-hua Shi, Hua-yu Hu, LI Yi, Sen Liu, *P.R. China*

Six hypervelocity impact tests of aluminum projectiles impacting aluminum plates were carried out. The range of projectile diameters was 2.0mm-5.0mm and the impact velocities varied from 3.0 km/s to 6.0 km/s. All the tests were normal impact. The atomic emission spectra of hypervelocity ejecta cloud are obtained by the instantaneous spectrometer. Six aluminum peaks and two concomitant peaks are identified in the emission spectrum. The effects of the concomitant peaks are analyzed and decoupled. Based on the spectral data, the ejecta cloud temperatures are analyzed using the Boltzmann diagram method and the configuration fitting method independently and the results are basically the same. The implication of the fact that the particle temperature of the ejecta cloud is uneven is discussed. It is found that for the uneven particles, the measurement result tends to be shifted toward the highest temperature of measuring time.

63 – EMI's TwinGun Concept for a New Light-Gas Gun Type Hypervelocity Accelerator

Robin Putzar, *Franhofer Institute for High-Speed Dynamics, Earnst-Mach-Institut, EMI;* Frank Schaefer, *Germany*

A new two-stage light-gas gun type accelerator was developed at Fraunhofer EMI. The accelerator features two parallel pump tubes that are attached to a single powder chamber. Loading conditions are adjusted to achieve a small delay between the arrival of the two pistons at their respective accelerated reservoir. A merging section combines both gas channels and guides the two pressure pulses generated to a single launch tube breech. The two pressure pulses merge to a single, but elongated pressure pulse that acts on the projectile. Carefully adjusting the loading conditions shall in the future increase the performance compared to standard light-gas gun accelerators. Initial experimental results of the calibre 4 mm prototype show feasibility of the concept.

30 – Down-Bore Velocimetry of an Explosively Driven Light-Gas Gun

Justin Huneault, *McGill University;* Jason Loiseau, Myles Hildebrand, Andrew Higgins, *Canada*

Hypervelocity launchers are used in a number science and engineering applications. The ability of the two-stage light-gas gun to launch relatively large and well characterized projectiles to hypervelocity has made it the launcher of choice for a wide range of hypervelocity impact research fields. However, practical concerns typically limit launcher operation to 8 km/s. This work will present the development of an explosively driven light-gas gun in which the linear implosion of a thin walled steel tube is used to dynamically compress helium gas, which subsequently expands to propel a projectile. Despite modest development efforts, the implosion-driven launcher has demonstrated the ability to launch a 0.36-g projectile to 10.4 km/s. This study will focus on a down-bore velocimetry experiment of an implosion-driven launcher using a photonic Doppler velocimetry system which was able to track the projectile velocity up to 7.8 km/s. The observed projectile acceleration is significantly higher than internal ballistic model predictions. It is proposed that mixing of ablated wall material with the light gas in the launcher driver is responsible for the anomalously high projectile acceleration.

36* – Development of Micro-Particles Accelerator with Pulse Formation

Takumi Kikuta, *Kyushu Institute of Technology;* Takaaki Uchino, Naoki Akao, Yasuhiro Akahoshi, Takao Koura, *Japan*

Space debris is one of major problems for recent space developments. When micro-debris of several hundred in diameter impacts spacecrafts, it may cause mission interruption. To design a safe and reliable space craft, we have to evaluate the risk of micro-debris impact by conducting ground-based hypervelocity impact experiments. To achieve these objectives, this study deals with the development of a plasma gun in which a plasma is created by applying high current and then accelerated by its own diffusion and Lorentz force. We think that it is important for accelerating projectiles to a higher velocity to shorten the current rise time and with a high plasma density. Therefore, to increase the velocity of the projectile, we examined the influence of the rise time and the plasma density. We conducted the experiments by a plasma gun and a WCR (Weak Current Removal) circuit to shorten the rise time and a short plasma gun to obtain a high-density plasma. These experimental results showed that it is necessary for accelerating to increase the maximum electric current, to adjust shooting the plasma to the peak time of the current and to increase the density of plasma.

Technical Session 9:

Spacecraft Meteoroid/ Debris Shielding and Failure Analyses II

(*denotes Poster Session)

65 – Time-resolved Spectroscopy of Plasma Flash from Hypervelocity Impact on DebriSat

Gouri Radhakrishnan, *The Aerospace Corporation, USA*

Time-resolved spectroscopic measurements were made on the intense plasma flash that accompanied a hypervelocity impact on "DebriSat" conducted in April 2014 at the Arnold Engineering Development Complex (AEDC) in Tennessee. The DebriSat project was a unique hypervelocity event aimed at simulating an on-orbit destructive collision of a modern satellite with a hypervelocity projectile in a single strike. Collaborators on the project included NASA's Orbital Debris Program Office at NASA Johnson Space Center (JSC), US Air Force Space and Missile Systems Center (SMC), The Aerospace Corporation, The University of Florida, and AEDC. The primary hypervelocity test object, DebriSat, was a 56 kg structure representative of a modern LEO spacecraft, assembled at University of Florida following design guidance provided by Aerospace's Concept Design Center. It comprised a hexagonal body with an arrangement of seven compartmentalized bays. The main panels and the structural ribs between the bays were constructed from Al 5052 honeycomb and carbon fiber composite face sheets. Each bay had a set of structures with components intended to represent those used in a modern satellite design. The AEDC projectile was a 570 g nylon-aluminum cylinder travelling at 6.8 km/s. An analysis of the first several frames of the DebriSat flash shows that the rate of radial expansion of the plume decreased from 4750 m/s at t = 0 to 2250 m/s at t = 156 µs. Time-resolved spectral measurements were conducted on the plasma flash with multiple frames acquired with a 10 µs gating interval. Numerous emission lines were observed and were consistent with the materials of structural components located in the specific bay of DebriSat that was impacted. A background was observed in all the spectral frames and could be fitted to a blackbody temperature of ~ 2900 K. A detailed description of the plasma flash and its spectroscopic investigation is presented.

75 – Investigation of S-SPH for Hypervelocity Impact Calculations

David Stowe, *Corvid Technologies;* Ryan Kupchella, Hua Pan, John Cogar, *USA*

In this paper, we investigate the Symmetric-SPH (S-SPH) method. S-SPH restores n-order consistency to the SPH formulation while remaining fully conservative by using a Taylor expansion of field variables to fit the kernel function. It has potential for HVI problems because it enables the ability to perform accurate stress and state calculations. We implement S-SPH in the Velodyne hydro-structural solver and evaluate its performance over a series of numerical examples including flyer impact, fragment penetration, and Taylor Rod impact. Idealized contact algorithms are employed to eliminate uncertainty in the flyer and Taylor impact problems while an advanced Lagrange multiplier algorithm is used for the fragment penetration test. We use the CTH hydrocode to provide a baseline response for each of the examples due to its ability to effectively handle penetration, hydrodynamic deformation, and shock propagation. Direct numerical comparisons are used to eliminate uncertainty from material characterizations, equation of state (EOS) models, and mesh resolution. We identify strengths and shortcomings of the S-SPH method and evaluate its utility for classes of HVI problems. We also compare the performance against SPH to compare relative accuracy, computational cost, and stability.

57 – Response of a Wire Probe Antenna Subjected to Hyper-Velocity Impacts

Kumi Nitta, *Japan Aerospace Exploration Agency;* Masumi Higashide, Atsuhi Takeba, Masahide Katayama, *Japan*

We investigated the effect of hypervelocity impacts of micrometeoroids and small-scale orbital space debris (M/OD) on space structures by comparing numerical simulation results obtained using the AUTODYN-3D hydrocode with the results of experiments using a two-stage light gas gun. We compared numerical simulations with experimental results and investigated the response of a Wire Probe anTenna (WPT) wire subjected to high-velocity impacts. We show the response of the WPT wire hypervelocity impacts from 2 km/s up to 15 km/s. We also verified the Ballistic limit curve of WPT wire is shown the downside line.

62 – Orbital Debris Assessment Testing in the AEDC Range G

Marshall Polk, *USAF*, David Woods, Brian Roebuck, John Opiela, Patti Sheaffer, Jer-Chyi Liou, *USA*

The space environment presents many hazards for satellites and spacecraft. One of the major hazards is hypervelocity impacts from uncontrolled man-made space debris. Arnold Engineering Development Complex (AEDC), the National Aeronautics and Space Administration (NASA), the United States Air Force Space and Missile Systems Center (SMC), the University of Florida, and the Aerospace Corporation configured a large ballistic range to perform a series of hypervelocity destructive impact tests in order to better understand the effects of space collisions. The test utilized AEDC's Range G light gas launcher, which is capable of firing projectiles up to 7 km/sec. A nonfunctional full-scale representation of a modern satellite called the DebriSat was destroyed in the enclosed range environment. Several modifications to the range facility were made to ensure quality data was obtained from the impact events. The facility modifications were intended to provide a high-impact energy-to-target-mass ratio (>200 J/g), a nondamaging method of debris collection, and an instrumentation suite capable of providing information on the physics of the entire impact event.

25 – Comparison of Aluminum Alloy and CFRP Bumpers for Space Debris Protection

Masumi Higashide, *Japan Aerospace Exploration Agency;* Takumi Kusano, Yuu Takayanagi, Kazuyoshi Arai, Sunao Hasegawa, *Japan*

The important components of a spacecraft require protective shielding from space debris impact. However, shields increase the total weight of a spacecraft. Carbon fiber reinforced plastic (CFRP) is well known as a high-strength and light-weight material. The purpose of this study is to evaluate availability of CFRP bumper shields. The kinetic energies of the debris clouds generated from the bumpers were focused on. Hypervelocity impact experiments were conducted on aluminum alloy and CFRP bumpers. Based on the results of preliminary experiments, it was possible to identify the origin of a crater on a witness plate as being aluminum or CFRP by examining the crater surface. The kinetic energies of fragments in debris clouds were calculated using debris cloud images captured with a high speed camera and the results of microscopic examination of craters on witness plates. When the CFRP bumper had larger thickness than the projectile diameter, the CFRP bumper seemed to reduce the kinetic energy of debris cloud than the aluminum alloy bumper. Consequently, CFRP debris bumper is considered to show availability if debris smaller than the bumper thickness impacts on the bumper.

52* – Multi-Shock Shield Performance At 14 MJ for Catalogued Debris

Joshua Miller, *University of Texas at El Paso and NASA Johnson Space Center;* YEric Christiansen, Bruce Davis, Dana Lear, Jer-Chyi Liou, *USA*

Increasingly asymmetric conflicts within urban terrains are requiring not only a high precision weapon system but also a munition with large flexibility in performance. Today's warheads don't have these capabilities resulting in a significantly reduced freedom of action. During the last decade TDW put a lot of effort into the research of new warhead technologies trying to change this inappropriate situation. In previous papers the very first ideas meeting these challenges were presented. In the meantime further progress was achieved leading to new warhead concepts. A radially Switchable Modes Warhead (SMW) and a Scalable Effects Warhead (SEW) were discussed. Finally two other concepts now on axially Switchable Modes Warheads were presented (see also references). In the current paper an idea on radially performing warheads already shortly discussed in a previous work was resumed and will be further pursued in this work. An internal layer was used in this study to influence the performance of the fragmenting casing thus making the warhead tunable.

70* – A First-Principles-Based Model for Crack Formation in a Pressurized Tank Following an MMOD Impact

William Schonberg, *Missouri University of Science and Technology;* J. Martin Ratliff, *USA*

Most robotic spacecraft have at least one pressurized vessel on board, usually a liquid propellant tank. One of the design considerations of such spacecraft is the anticipation and mitigation of the possible damage that might occur from on-orbit impacts by micro-meteoroids or orbital debris (MMOD). While considerable effort has been expended in the study of the response of non-pressurized spacecraft components to MMOD impacts, relatively few studies have been conducted on the pressurized elements of such spacecraft. In particular, since it was first proposed nearly 45 years ago, NASA's current evaluation methodology for determining impact-induced failure of pressurized tanks has undergone little scrutiny. This paper presents a first-principles based model that has been developed to predict whether or not cracking might start or a through-crack might be created under an impact crater in a thin plate. This model was used to examine the effect of penetration depth on crack formation and whether or not the crack might grow through the tank wall thickness. The predictions of the model are compared to experimental data with encouraging results. The paper also develops some suggestions for future work in this area, including the extension of the first-principles model to include 3-D crack initiation modelling.

Technical Session 10:

Asteroid Impact and Planetary Defense Technology I

(*denotes Poster Session)

26 – Momentum Transfer in Hypervelocity Impact Experiments on Rock Targets

Tobias Hoerth, *Fraunhofer EMI;* Frank Schäfer, Jan Hupfer, Oliver Millon and Matthias Wickert, *Germany*

A special phenomenon observed in hypervelocity impacts on rock targets is the so-called momentum multiplication, i.e. the momentum transferred to the target is greater than the original momentum of the projectile. This effect is caused by ejection of debris in the direction opposite to the flight direction of the projectile. In the present study momentum multiplication was investigated as a function of target material properties and projectile velocity. Hypervelocity impact experiments on target materials with different porosities were conducted and the momentum transfer was measured using a ballistic pendulum. Low porous materials like quartzite show larger momentum multiplication than porous materials like sandstone. The smallest momentum multiplication was measured for highly porous aerated concrete. Higher projectile velocity leads to higher momentum multiplication. Furthermore, this increase is stronger for low porous materials compared with porous materials. These observations can be explained by the different ejection behavior. Low porous materials show a directional and very fast ejection whereas porous materials show a slower ejection. The highly porous material shows a diffuse ejection behavior. Furthermore, cratering efficiency is reduced in porous targets leading to a smaller amount of ejected debris. This effect is attributed to energy dissipation caused by irreversible crushing of pore space

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27 – Dynamic Brittle Fragmentation: Probing the Byproducts of Hypervelocity Impact in Space

James Hogan, *Hopkins Extreme Materials Institute;* Charles El Mir, Jeffrey Plescia, KT Ramesh, *USA*

Improvements in computational and analytical modelling of large-scale impact and catastrophic disruption events will come from a better understanding of the failure processes that are active during high strain-rate events. In this study we investigate the dynamic compressive failure and fragmentation of basalt, paying particular attention to the role each constituent mineral phase has in these processes. Our results indicate the existence of two fragmentation mechanisms: I. a mechanism that creates small fragments that is associated with the spacing of critically activated defects. These fragments are primarily comprised of pyroxene (which has the lowest fracture toughness in this material). II. a mechanism related to larger fragments that is associated with the structural failure of the sample. These fragments are primarily polyphase and polygrain in composition. In the second part of the paper, we investigate the strength of fragmented basalt material for different initial fragment size distributions: 1. between 10 and 100 microns, 2. between 200 and 800 microns, and 3. between 300 and 1,800 microns. The porosity of each of the three samples was maintained between 30 and 35 %. Understanding the composition of the fragments beforehand allows us to better interpret our experimental results, which indicate that the strengths of the fragmented material increased with decreasing fragment sizes, from 4 to 25 MPa, and then to 175 MPa. An increase in strength with smaller fragment sizes is expected because of the associated increase in frictional dissipation, and decrease in the relative contribution of compaction and fracturing mechanisms. However, we do note that fragments less than 100 microns fail as a result of the activation of a different critical defect type than in the bulk material and for fragments larger than 100 microns, where olivine grains are the key contributors to fracture. Altogether, these results highlight the influence of the composition and defect population of planetary materials on the associated length scales that arise from dynamic failure and fragmentation.

40 – Remnants of Early Archean Impact Deposits on Earth: Search for a Meteoritic Component in the BARB5 and CT3 Drill Cores (Barberton Greenstone Belt, South Africa)

Christian Koeberl, *University of Vienna;* Toni Schulz, Uwe Reimold, *Austria and Germany*

The first 2.5 billion years of the terrestrial impact history are not documented by any impact structures. Only a few spherule layers of impact origin are known, most of them of late Archean to early Proterozoic age. In the Barberton Greenstone Belt (South Africa), several spherule horizons (layers S1 to S4, possibly up to S8, with ages between ~3.5 and ~3.2 Ga) are amongst the oldest deposits from large bolide impacts onto Earth. Impact evidence is limited to (highly) elevated siderophile element contents and Cr isotopic compositions. Other isotope tools, such as the 187Re-188Os radionuclide system in combination with high-precision concentration data for siderophile elements, might be useful to confirm the propositions regarding the presence of meteoritic components made so far. Two recently recovered drill cores from the central and northern Barberton area (CT3 and BARB5) with as many as 18 spherule layer intersections of Paleoarchean age (some of which may be due to tectonic duplication, some might correlate with the S2 to S4 layers) provide an outstanding opportunity to gain new insight into the early impact bombardment of Earth. We present new mineralogical, chemical, and 187Re-188Os isotope data on CT3 and BARB5 drill core samples. Spherules in most layers exhibit undeformed shapes and include vesicles. Sulfides frequently are present in both matrix and spherules. Osmium data reveal a trend between the spherule-free horizons (intercalating the spherule layers) and spherule-matrix aggregates. Whereas the former typically exhibit elevated 187Os/188Os ratios of up to ~1.2 and low Os and Ir concentrations below several hundred ppt, spherule-matrix aggregates tend to be less radiogenic (down to subchondritic present day 187Os/188Os ratios) with Os and Ir concentrations as high as in chondrites. Chromium-Ir correlations for CT3 and BARB5 samples mirror earlier results on S1 to S4 layers and can be interpreted in favor of an impact origin of the here investigated spherule horizons.

22 – Deep Impact – A Review of the World's Pioneering Hypervelocity Impact Mission

Monte Henderson, *Ball Aerospace;* William Blume, *USA*

On July 4th, 2005, in celebration of our nation's birthday, NASA's Deep Impact Impactor spacecraft collided with comet Tempel1 at 10km/sec – marking the first hypervelocity impact of a celestial body by a human-made spacecraft. With closing speeds of 23,000 mph, the Impactor's active guidance system steered it to impact on a sunlit portion of the comet's surface. As it closed in on Tempel 1, the Impactor's camera relayed close-up images of the comet's surface to the Flyby spacecraft for downlink to Earth. Meanwhile, the Flyby spacecraft used its two instruments to image the impact and then continued to photograph the comet as it followed its orbital path around the Sun. The primary science data was returned to Earth in near real-time, and all data was returned to Earth within 24 hours of the encounter. For the NASA Discovery-class Deep Impact mission, a two-part Deep Impact spacecraft was constructed: the Impactor spacecraft and the impact characterization (flyby) spacecraft, and an associated suite of surveillance instruments. These instruments included one high resolution visible imager, two identical medium-resolution visible imagers (one on the flyby and one on the Impactor) and one infrared spectrometer. The two-part spacecraft launched together in January 12, 2005 and separated on July 3rd, 24 hours before reaching its Tempel 1 target. The Impactor separated from the flyby spacecraft and autonomously positioned itself directly in front of the encroaching Tempel 1 comet for a spectacular hypervelocity impact.

74 – Modeling Momentum Transfer from Kinetic Impacts: Implications for Redirecting Asteroids

Angela Stickle, *Johns Hopkins University Applied Physics Laboratory;* Justin Atchison, Olivier Barnouin, Andrew Cheng, David Crawford, Carolyn Ernst, Zachary Fletcher, Andy Rivkin, *USA*

Kinetic impactors are one way to deflect a potentially hazardous object headed for Earth. The Asteroid Impact and Deflection Assessment (AIDA) mission is designed to test the effectiveness of this approach and is a joint effort between NASA and ESA. The NASA-led portion is the Double Asteroid Redirect Test (DART) and is composed of a ~300-kg spacecraft designed to impact the moon of the binary system 65803 Didymos. The deflection of the moon will be measured by the ESA-led Asteroid Impact Mission (AIM) (which will characterize the moon) and from ground-based observations. Because the material properties and internal structure of the target are poorly constrained, however, analytical models and numerical simulations must be used to understand the range of potential outcomes. Here, we describe a modeling effort combining analytical models and CTH simulations to determine possible outcomes of the DART impact. We examine a wide parameter space and provide predictions for crater size, ejecta mass, and momentum transfer following the impact into the moon of the Didymos system. For impacts into "realistic" asteroid types, these models produce craters with diameters on the order of 10 m, an imparted Δv of 0.5–2 mm/s and a momentum enhancement of 1.07 to 5 for a highly porous aggregate to a fully dense rock.

6* – FEMA Asteroid Impact Tabletop Exercise Simulations

Mark Boslough, *Sandia National Laboratories & University of New Mexico;* Barbara Jennings, Brad Carvey, William Fogleman, *USA*

We describe the computational simulations and damage assessments that we provided in support of a tabletop exercise (TTX) at the request of NASA's Near-Earth Objects Program Office. The overall purpose of the exercise was to assess leadership reactions, information requirements, and emergency management responses to a hypothetical asteroid impact with Earth. The scripted exercise consisted of discovery, tracking, and characterization of a hypothetical asteroid; inclusive of mission planning, mitigation, response, impact to population, infrastructure and GDP, and explicit quantification of uncertainty. Participants at the meeting included representatives of NASA, Department of Defense, Department of State, Department of Homeland Security/Federal Emergency Management Agency (FEMA), and the White House. The exercise took place at FEMA headquarters. Sandia's role was to assist the Jet Propulsion Laboratory (JPL) in developing the impact scenario, to predict the physical effects of the impact, and to forecast the infrastructure and economic losses. We ran simulations using Sandia's CTH hydrocode to estimate physical effects on the ground, and to produce contour maps indicating damage assessments that could be used as input for the infrastructure and economic models. We used the FASTMap tool to provide estimates of infrastructure damage over the affected area, and the REAcct tool to estimate the potential economic severity expressed as changes to GDP (by nation, region, or sector) due to damage and short-term business interruptions.

11* – Terrestrial Carbonaceous Debris Tracing Atmospheric Hypervelocity-Shock Aeroplasma Processes

Marie-Agnès Courty, *CNRS UPR 8521;* Jean-Michel Martinez, *France*

Atmospheric hypervelocity impacts are widely viewed to produce the meteoric smoke layer by the shock-less interactions of the impinging air molecules with the vaporized meteoroid. In contrast here, we intend to show how gas and solid aerosols when captured in the Mach cone of a bolide while entering the Earth atmosphere are transformed into a new range of polymeric nanomaterials. Carbonaceous materials from natural situations are studied from collect in a pilot region of Southern France in the following days of a high altitude meteor atmospheric airburst on 2011 August 2nd and since the 2013 February 15th Chelyabinsk meteoritic event in Ural. These materials are compared to the ones obtained by hypervelocity shock with the CEA Persephone light-gas gun. A numerical simulation with the Tycho software is performed to model the evolution of the increase of density directly in the rear front of the shockwave with the increase of velocity around an obstacle for high velocity inflow. The multidisciplinary approach reveals the production carbon-based nanosolids from terrestrial precursors by hypervelocity plasma particle deposition (HPPD) processes. The Tycho simulation helps to establish the lack of mixing between the ablation smoke and the surrounding atmosphere. The correlation between the simulation, the hypervelocity experiments and the natural situations shows the distinctive characteristics of visco-elastic filamentary nanosolids formed in the laminar domain of low pressure, the ones of nanoparticle-rich stiff film specific to the thin domain of high shear stress and the ones of dense glassy carbon with nanocarbon crystallites (graphite and graphene-like) only formed in the frontal high temperature and pressure domain. Data on the natural carbon-based nanosolids indicate that the atmospheric shock-dissociation occurred from a carbon pool dominated by dead atmospheric carbon. Diagnostic keys are provided to distinguish natural carbon-based nanosolids synthesized by HPPD just at the time of the hypervelocity atmospheric entry from their subsequent transformations during atmospheric transport by other aeroplasma processes.

15* – Simulation of Asteroid Impact on Ocean Surfaces, Subsequent Wave Generation and the Effect on US Shorelines

Souheil Ezzedine, *Lawrence Livermore National Laboratory;* Ilya Lomov, Paul Miller, Deborah Dennison, David Dearborn, Tarabay Antoun, *USA*

As part of a larger effort involving members of several other organizations, we have conducted numerical simulations in support of emergency-response exercises of postulated asteroid ocean impacts. We have addressed the problem from source (asteroid entry) to ocean impact (splash) to wave generation, propagation and interaction with the U.S. shoreline. We simulated three impact sites. The first site is located off the east coast by Maryland's shoreline. The second site is located off of the West coast, the San Francisco bay. The third set of sites are situated in the Gulf of Mexico. Asteroid impacts on the ocean surface are conducted using LLNL's hydrocode GEODYN to create the impact wave source for the shallow water wave propagation code, SWWP, a shallow depth averaged water wave code. The GEODYN-SWWP coupling offers unique capabilities to address the full scale interactions of asteroids with the ocean and the interactions of the water waves with the shorelines.

68* – Laboratory Impact Experiments to Study Asteroid Collisional Disruption as a Function of Size and Shape in the Strength Regime

Heidi Stange-Love, *New Mexico Institute of Mining and Technology;* Eileen Ryan, *USA*

Laboratory impact experiments on meter-scale targets were conducted to explore collisional outcomes pertinent to the problem of hazardous asteroid mitigation. In particular, the primary aim of the experiments was to improve our understanding of how the energy needed to fragment and disrupt an asteroid scales with size, such that mitigation strategies could better incorporate this parameter. Previous researchers found that this critical disruption energy decreased with increasing target size. A secondary goal of the research was to investigate post-impact other factors that might be affected by target size-scaling such as ejecta translational and rotational velocities. Preliminary results will be presented for these parameters such that comparisons to the asteroid population can be made in the future.

81* – Damage Modeling, Scaling and Momentum Enhancement for Asteroid and Comet Nucleus Deflection

James D. Walker, *Southwest Research Institute;* Sidney Chocron, *USA*

In the previous symposium, it was demonstrated that extrapolation of momentum enhancement Φ data from small laboratory tests to larger asteroid and comet nucleus deflection scenarios predicts large Φ values due to the fact that Φ does not scale with size. The big question in the extrapolation to larger scales is whether the damage process in the crater formation saturates at some scale – i.e., is there a size beyond which the momentum enhancement does scale, and thus the large scale large Φ values are not realized. In this work we take the data from the NASA Ames gun in the 1960s by Denardo and Nysmith [1] and examine its clear lack of scaling in more detail. We determine the behavior of the ejecta mass. We show that the amount of ejecta mass is proportional to the impact velocity squared times the square root of the projectile diameter, a quantity which has the dimensions of fracture toughness. Thus, it is likely that the mass liberation process depends on fracture toughness, which contrasts with the fact that the crater size depends on target material strength. Thus, a small fracture toughness leads to large ejecta mass, and that in turn leads to large momentum enhancement. The appearance of the dimensions of fracture toughness implies that classical failure scaling is at work. Classical fracture mechanics is a damage process that likely will not saturate and that we then are able to extrapolate to large sizes. We discuss impactors that would be used to deflect asteroids or comet nuclei for planetary defense or for engineering and exploration purposes, and what expected momentum enhancements would be for impacts into asteroids or comet nuclei comprised of consolidated materials.

Technical Session 11:

Asteroid Impact and Planetary Defense Technology II

(*denotes Poster Session)

9 – Facing a Hypervelocity Asteroid Impact Disaster: To Deflect or Evacuate?

Clark R. Chapman, *Department of Space Studies, Southwest Research Institute, USA*

Understanding of the near-Earth asteroid impact hazard has been evolving. As larger near-Earth objects (NEOs) are retired from concern by the Spaceguard Survey, as new search strategies oriented toward short-term warning are brought on line, as we understand the increasing danger from NEOs in the 15 m to 40 m size range, and in the aftermath of the 2013 Chelyabinsk impact disaster, attention necessarily must shift toward dealing with the most likely dangerous impacts, those in the range of Chelyabinsk to Tunguska. Appropriate responses to predicted impacts by smaller NEOs involve civil defense and emergency planning endeavors. Deflection of an NEO's trajectory by spacecraft impact, or other means, is becoming a less likely type of mitigation than evacuation. We need more research on the environmental and human consequences of diverse types of hypervelocity NEOs interacting with the Earth's atmosphere, oceans, and land surfaces.

86 – Orbital Simulations for Directed Energy Deflection of Near-Earth Asteroids

Qicheng Zhang, *University of California, Santa Barbara;* Kevin J. Walsh, Carl Melis, Gary B. Hughes, Philip Lubin, *USA*

Directed energy laser ablation at the surface of an asteroid or comet produces an ejection plume that will impart a thrust on the asteroid. This thrust can mitigate a threatened collision with the Earth. This technique uses the asteroid itself as the deflection propellant. The DE-STAR laser system is designed to produce a sufficiently intense spot on the surface of an asteroid to accomplish this in one of two operational modes. One is a complete "stand-off" mode where a large space based phased-array laser directed energy system can interdict asteroids at large distances allowing sufficient time to mitigate nearly all known threats. A much smaller version of the same system, called DE-STARLITE, can be used in a "stand-on" mode by taking a much smaller laser to the asteroid and slowly deflecting it over a sufficiently long period of time. Here we present orbital simulations for a range of near-Earth asteroid impact scenarios for both the stand-off and stand-on systems. Simulated orbital parameters include asteroid radius and composition, initial engagement time, total laser-on time and total energy delivered to target. The orbital simulations indicate that, for exposures that are less than an orbital time, the thrust required to divert an asteroid is generally inversely proportional to laser-on time, proportional to target mass and proportional to the desired miss distance. We present a detailed stand-on scenario, consistent with current dedicated mission capabilities, to show the potential for laser ablation to allow significant deflection of targets with small systems. As one example we analyze a DE-STARLITE mission scenario that is in the same mass and launch envelope as the proposed Asteroid Redirect Mission (ARM) but using a multi kilowatt class laser array capable of deflecting a 325 m diameter asteroid with 2N of thrust for 15 years in a small fraction of even the smallest SLS block 1 launch vehicle configuration.

23 – Simulations of Defense Strategies for Bennu: Material Characterization and Impulse Delivery

Eric Herbold, *Lawrence Livermore National Laboratory;* John Owen, Damian Swift, Paul Miller, *USA*

Assessments of asteroid deflection strategies depend on material characterization to reduce the uncertainty in predictions of the deflection velocity resulting from impulsive loading. In addition to strength, equation of state, the initial state of the material including its competency (i.e. fractured or monolithic) and the amount of micro- or macroscopic porosity are important considerations to predict the thermomechanical response. There is recent interest in observing near-Earth asteroid (101955) Bennu due to its classification of being potentially hazardous with close approaches occurring every 6 years. Bennu is relatively large with a nominal diameter of 492 m, density estimates ranging from 0.9-1.26 g/cm3 and is composed mainly of carbonaceous chondrite. There is a lack of data for highly porous carbonaceous chondrite at very large pressures and temperatures. In the absence of the specific material composition and state (e.g. layering, porosity as a function of depth) on Bennu we introduce a continuum constitutive model based on the response of granular materials and provide impact and standoff explosion simulations to investigate the response of highly porous materials to these types of impulsive loading scenarios. Simulations with impact speeds of 5 km/s show that the shock wave emanating from the impact site is highly dispersive and that a 10% porous material has a larger compacted volume compared with a 40% porous material with the same bulk density due to differences in compaction response. A three-dimensional simulation of a 190 kT standoff explosion 160 m off the surface of a shape model of Bennu estimated a deflection velocity of 10 cm/s.

20 – Spacecraft for Hypervelocity Impact Research – An Overview of Capabilities, Constraints and the Challenges of Getting There

Jan Thimo Grundmann, *DLR German Aerospace Center Institute of Space Systems;* Bernd Dachwald, Christian D. Grimm, Ralph Kahle, Aaron Dexter Koch, Christian Krause, Caroline Lange, Dominik Quantius, Stephan Ulamec, *Germany*

We present an introductory overview of the capabilities, constraints and challenges to be taken into account in the design of space missions for HVI research and application, focusing on related planetary defense applications, small spacecraft approaches, using our activities and projects as examples. Large lightweight deployable structure applications are discussed, for large-scale photovoltaic arrays in advanced solar-electric propulsion missions, and for solar sailing as a non-fuel-constrained method of achieving high-energy or retrograde orbit and multiple target missions. Small asteroid landers are discussed as vehicles for precursor exploration of impact target asteroids, precision target orbit determination, and for impact process monitoring that also can be deployed from sail-based missions.

59 – Asteroid Diversion Considerations Comparisons Diversion Techniques

Michael Owen, *Lawrence Livermore National Laboratory;* Paul Miller, Jared Rovny, Joe Wasem, Kirsten Howley, Eric Herbold, *USA*

The threat of asteroid impacts on Earth poses a low-probability but high consequence risk, with possible outcomes ranging from regional to global catastrophe. However, unique amongst such global threats we have the capability of averting such disasters. Diversion approaches by either kinetic impactor or nuclear energy deposition are the two most practical technologies for mitigating hazardous near Earth asteroids. One of the greatest challenges in understanding our options is the uncertain response of asteroids to such impulsive techniques, due both to our lack of knowledge of the composition and structure of these objects as well as their highly varied nature. Predicting whether we will simply divert or break up a given object is a crucial: the weak self-gravity and inferred weak structure of typical asteroids present the strong possibility the body will fragment for modest impulses. Predictive modeling of failure and fragmentation is one important tool for such studies. In this paper we apply advances in modeling failure and fracture using Adaptive Smoothed Particle Hydrodynamics (ASPH) to understand mega-cratering on asteroids as a validation exercise, and show examples of diverting the near Earth asteroid Bennu using both a kinetic impactor and ablative blow-off due to nuclear energy deposition.

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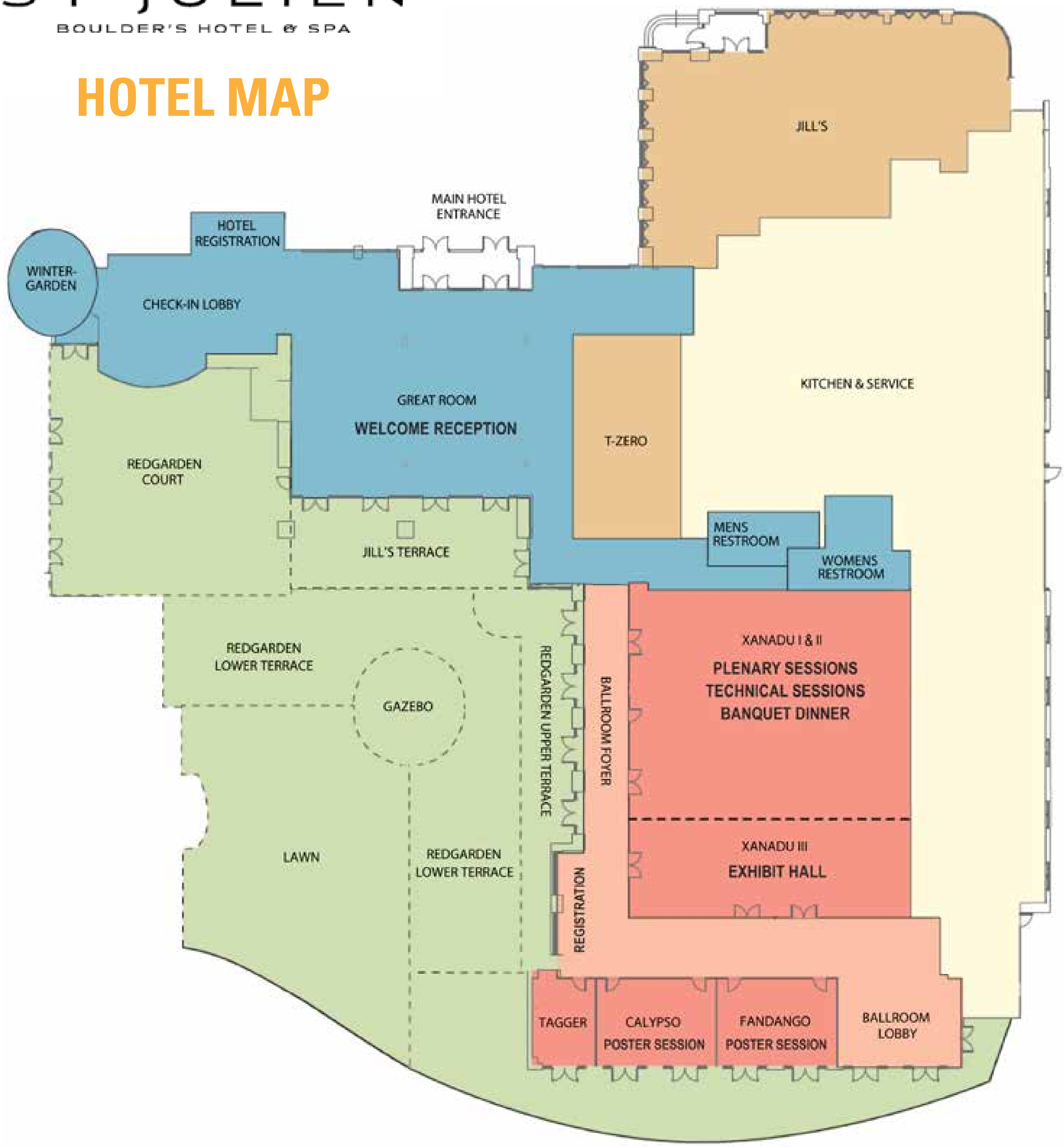
BOULDER'S HOTEL & SPA

HOTEL MAP



H V I S

Companion Program

Monday, April 27, 2015

Morning Tour

Celestial Seasonings Tea Factory Tour

From raw ingredients to finished products, you'll learn all about the wonderful world of tea and see how products are blended, packaged and shipped. You'll never look at tea the same way again!

Lunch

Celestial Seasonings Café

at your own expense

The Celestial Café serves fresh, nutritious, home-cooked meals in a warm and inviting atmosphere filled with beautiful Celestial Seasonings artwork.

Afternoon Excursion

Leanin' Tree Museum of Western Art

The Leanin' Tree Museum of Western Art exhibits the private art collection of Ed Trumble, Founder and Chairman of Leanin' Tree, publisher of fine art greeting cards since 1949. His collection was born of a passion for American western art that has spanned seven decades.

Dinner

Rembrandt Yard

dinner ticket required

No children allowed under age 16.

Tuesday, April 28, 2015

Breakfast/Morning Adventure

The Boulder Dushanbe Teahouse

at your own expense

Sitting alongside Boulder Creek in Central Park, the Teahouse is considered one of Boulder's most attractive and popular tourist attractions, as well as being a local favorite for great food, tea, and atmosphere.

Explore Pearl Street

Come enjoy the beautiful Pearl Street Mall, Pearl Street's East End & West End and everywhere else in between, with upwards of 1,000 businesses (85 percent of which are locally owned and operated).

Lunch

The Kitchen

at your own expense

The Kitchen is a community bistro located in historic downtown Boulder, Colorado.

Afternoon

Explore Boulder, Colorado

on your own

Wednesday, April 29, 2015

Morning

Explore Boulder, Colorado

on your own

Lunch

Chautauqua Dining Hall

at your own expense

The Chautauqua Dining Hall has been a Boulder tradition since 1898. Savor spectacular views from the enchanting wraparound porch while enjoying fresh, Colorado bistro cuisine. Open daily year-round, the Dining Hall offers a full bar with local beers and great wines to complement your meal.

Dinner

Symposium Banquet Dinner

St. Julien Hotel, Xanadu I & II

dinner ticket required

WELCOME TO BOULDER! | Top Things to Do

Eat & Drink

Boulder was named ***America's Foodiest Town*** *by Bon Appétit* magazine and Pearl Street is one of the ***10 Best Foodie Streets*** *in America* according to *Food & Wine*. We are also one of the nation's beer meccas with 20 breweries and counting.

Get Outside

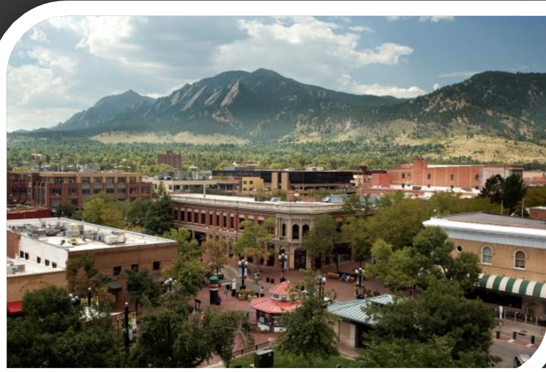
The pine breezes are fresh and the views striking from just about anywhere in Boulder. Get out and enjoy it by biking or walking the **Boulder Creek Path**, which runs right through town. Or head to **Chautauqua Park**, where you can hike among the famous **Flatirons** — or simply take pictures.

Shop Local

Boulder's shopping scene is undergoing a renaissance! There is a rash of new boutiques (and even megastores like H&M), perfect for the shopaholic. Start on historic downtown's **Pearl Street Mall** and then to **Twenty Ninth Street** for dozens of chain and local shops.

Can't-Miss Attractions

Take a free tour at major tea manufacturer **Celestial Seasonings**, where you'll enjoy free tea tastings — and, of course, the famous mint room. A variety of tours will help you get the inside scoop on the Boulder lifestyle: guided **walking tours**; a fun **bus tour**; **foodie, winery, brewery, distillery tours**; or **hiking** tours. There's plenty of art and culture, too. You won't have to look hard to find **street performers**, **galleries**, **museums**, **orchestras**, and **rockin' live music**.



Did You Know? Boulder Is...

- **easily walkable**, with a compact, historic downtown
- just **45 minutes from Denver International Airport (DIA)**
- just **30 minutes from Denver**
- **a top city for tech startups** with an atmosphere of innovation
- **No. 3 best city for biking**, according to Bicycling magazine
- **one of the happiest and healthiest cities in the U.S.**, according to an annual Gallup poll

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H • V • I • S

The 2015 HVIS Symposium is organized by the Hypervelocity Impact Society in coordination with Missouri S&T.

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