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Survey of the Hypervelocity Impact Technology and Applications

Lalit Chhabildas and Dennis Orphal

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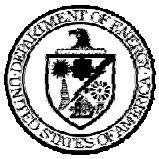

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Survey of the Hypervelocity Impact Technology and Applications

A Report to the U.S. Army Research Laboratory

Lalit C. Chhabildas and Dennis L. Orphal
HVIS 2005 Hypervelocity Impact Symposium
October 9-13, 2006
Lake Tahoe, California

Executive Summary

HVIS 2005 was a clear success. The Symposium brought together nearly two hundred active researchers and students from thirteen countries around the world. The 84 papers presented at HVIS 2005 constitute an "update" on current research and the state-of-the-art of hypervelocity science. Combined with the over 7000 pages of technical papers from the eight previous Symposia, beginning in 1986, all published in the International Journal of Impact Engineering, the papers from HVIS 2005 add to the growing body of knowledge and the progressing state-of-the-art of hypervelocity science.

It is encouraging to report that even with the limited funding resources compared to two decades ago, creativity and ingenuity in hypervelocity science are alive and well. There is considerable overlap in different disciplines that allows researchers to leverage. Experimentally, higher velocities are now available in the laboratory and are ideally suited for space applications that can be tied to both civilian (NASA) and DoD military applications. Computationally, there is considerable advancement both in computer and modeling technologies. Higher computing speeds and techniques such as parallel processing allow system level type applications to be addressed directly today, much in contrast to the situation only a few years ago. Needless to say, both experimentally and computationally, the ultimate utility will depend on the curiosity and the probing questions that will be incumbent upon the individual researcher. It is quite satisfying that over two dozen students attended the symposium. Hopefully this is indicative of a good pool of future researchers that will be needed both in the government and civilian industries. It is also gratifying to note that novel thrust areas exploring different and new material phenomenology relevant to hypervelocity impact, but a number of other applications as well, are being pursued. In conclusion, considerable progress is still being made that is beneficial for continuous development of hypervelocity impact technology and applications even with the relatively limited resources that are being directed in this field.

HYPERVELOCITY IMPACT SOCIETY

The Hypervelocity Impact Society is devoted to the advancement of the science and technology of hypervelocity impact and related technical areas required to facilitate and understand hypervelocity impact phenomena. Topics of interest include experimental methods, theoretical techniques, analytical studies, phenomenological studies, dynamic material response as related to material properties (e.g., equation of state), penetration mechanics, and dynamic failure of materials, planetary physics and other related phenomena.

The objectives of the Society are to foster the development and exchange of technical information in the discipline of hypervelocity impact phenomena, promote technical excellence, encourage peer review publications, and hold technical symposia on a regular basis. It was sometime in 1985, partly in response to the Strategic Defense Initiative (SDI), that a small group of visionaries decided that a conference or symposium on hypervelocity science would be useful and began the necessary planning. A major objective of the first Symposium was to bring the scientists and researchers up to date by reviewing the essential developments of hypervelocity science and technology between 1955 and 1985. So 2005, marked the 20th anniversary of the "seeding" of the Hypervelocity Impact Symposia under the auspices of the Hypervelocity Impact Society. This Symposia – HVIS 2005 is now the ninth Symposium since that beginning. The papers presented at all the HVIS are peer reviewed and published as a special volume of the archival journal *International Journal of Impact Engineering*. The eight previous HVIS proceedings contain nearly 7,000 pages of peer reviewed hypervelocity research papers. HVIS 2005 followed the same high standards and its proceedings will add to this enduring body of work.

HYPERVELOCITY IMPACT SYMPOSIUM

The 2005 Hypervelocity Impact Symposium (HVIS 2005) was the ninth in the "modern" series and was held October 9-13, 2005 at the Resort at Squaw Creek in California. Lalit Chhabildas from Sandia National Laboratories and Dennis Orphal from International Research Associates took the lead as co-chairman for symposium. A technical committee was established to assist with the organization of the symposia. The make up of the technical committee was diverse and consisted of well-reputed international scientists who are experts in their specialty. A list of the technical committee is provided in Appendix A.

We received a total of 148 abstracts from fifteen different countries. The technical committee recommended 100 abstracts for further consideration. 100 manuscripts were submitted and peer reviewed; all HVIS papers are peer reviewed for publication in the archival Journal - *International Journal of Impact Engineering* (IJIE). As a result of peer review, the technical committee selected only 84 papers for presentation at the meeting and for publication in the special volume of the IJIE. The guidelines used to select the manuscripts include the relevance, quality, and the originality of research representing hypervelocity impact phenomena. This special IJIE volume constitutes the Proceedings

for HVIS 2005, and thus the HVIS 2005 papers are archived for future reference. The special volume of the IJIE journal containing the papers from HVIS 2005 is expected to be published in the fall of 2006.

Total attendance at HVIS 2005 was 196 from 13 different countries. HVIS 2005 participants are listed in Appendix B. The 196 attendees included twenty-five students at a discounted registration rate. We make a significant effort to involve quality students as an investment in the future research and development of the technology. By this encouragement and help with expenses, we endeavor to provide the students with an incentive and a motivation for further career development in this discipline.

As indicated above a total of 84 papers were selected for presentation at the HVIS-2005. The symposia has a no paper – no podium policy, i.e., if the publishable journal article is not received on time, the authors are not allowed to present it at the symposia. Of these, 84 papers, 52 were presented orally and 32 were presented as posters. All oral papers are presented as plenary talks to ensure maximum exposure; the poster talks also get full exposure by scheduling and dividing those in between technical sessions everyday. In addition, four keynote lectures, including the HVIS Distinguished Scientist Award lecture, representing either a review of the literature and/or the current state of the art were also presented at the symposia.

TECHNICAL PAPERS

This report is an attempt to provide a brief summary of the technical findings and advances represented in the papers presented at HVIS 2005. The combination of this brief summary, along with the abstracts and the complete proceedings copy will constitute a review of the current state-of-the-art of hypervelocity science circa 2005. In addition to the regular technical sessions, four keynote lectures, including the distinguished scientist award, representing either a review of the literature and/or the current state of the art were also presented at the symposia.

The technical sessions for the HVIS 2005 were organized around the following technical topic areas. The number of papers in each topic area is given in parenthesis. The title of each paper is given in Appendix C

- Launchers and Diagnostics (12)
- Impact and Penetration (14)
- Material Response (17)
- Analytical and Numerical Computations (8)
- Debris Shielding (6)
- Fracture and Fragmentation (11)
- Planetary and Space (12)
- Phenomenology (4)

Dr. Lalit Chhabildas of Sandia National Laboratories received the HVIS Distinguished Scientist Award for 2005. The title of Dr. Chhabildas' Distinguished Scientist Award Lecture was: **Material EOS/Properties Measurements to Hypervelocity Launchers.**

The titles of the three other keynote addresses were as follows:

- **Fragmentation and Sir N. F. Mott**, *Dennis Grady*, Applied Research Associates,
- **The Fastest Magnetic Launcher – Macroscopic Plates to over 30 km/s - EOS Development and other Applications**, *Marcus Knudson*, Sandia National Laboratories
- **Deep Impact Mission**, *Peter Schultz*, Brown University

SUMMARY/HIGHLIGHTS OF THE SYMPOSIUM

Considerable progress has been made in the discipline of hypervelocity technology development and applications. There is considerable interest in the development of high speed launchers. Magnetic launchers (not a rail gun) have been developed that can accelerate plates to over 30 km/s. A time-dependent magnetic field is used to drive aluminum plates nominally 300 microns thick. Modified two-stage gun launchers also known as three stage light gas guns are being used to launch dust clouds to over 10 km/s; 1-mm size particles can be launched to around 19 km/s. Three stage gun launchers are also being designed to launch "spheres" to around 10 km/s. To date they have achieved around 8.7 km/s. The concept of using two two-stage light-gas gun throwing projectiles at each other is still being pursued. New two-stage light gas gun facilities are still being developed. There were a dozen papers on launchers presented at the meeting.

Many of these hypervelocity launcher developments are motivated by space applications – especially to investigate space debris impact on targets. Cryogenic techniques are also being interfaced to determine the effects of cold targets to space debris impact. The targets are designed to represent solar arrays, satellites, debris shields, single and multiple Whipple space bumpers, etc. There is also interest in determining effects of asteroid impacts on the earth – with applications to space defense. There were approximately half a dozen papers on space debris shielding.

Hypervelocity impact and penetration phenomenology is extremely varied. This topic area includes investigations tailored to address penetration phenomena in a variety of targets including metals, ceramics, composites, and geo-materials. The penetrators include long rods, and spheres. In particular penetrator shape effects, beyond simply long-rods vs. "chunky projectiles" is now being seriously investigated. Strength issues related to penetration continue to be studied. Strength of materials is determined directly to very high bar mega pressures. This includes ceramic and metallic targets. There were fourteen papers on penetration behavior capturing the above mentioned topics.

Fracture and fragmentation of materials has become a topic of major interest as reflected in the number of papers on this general topic at HVIS 2005. A dozen papers, including a

keynote address were identified to be presented under the general topic heading of Fracture and Fragmentation. And, this is a low estimate since there is considerable overlap as evidenced by the many of the papers on damage, material phenomenology, and debris shielding and penetration behavior. This topic is quite informative and discussions included, Mott's classic fragmentation criteria originated around WWII, the Butcher-Tuler model discussed in the early sixties, energy based fragmentation behavior, engineering models, behind armor debris and computational methods to implement fragmentation behavior. It is interesting to see how well these "classical" models compare with old as well as modern data. And at the same time it is very clear that much progress remains to be accomplished in understanding fracture and fragmentation of solids. It appears that there is interest developing in understanding fragmentation in liquids as well.

One of the areas that have shown considerable progress is in the topical area of analytical and numerical computations. With the availability of much improved material models combined with state of the art hydrodynamic (really continuum mechanics) or structural codes, and the development of high speed computational techniques (parallel processing), there is now an added incentive to view computational results in the same framework as experimental data. New numerical techniques are being developed. Some of the examples are molecular dynamics simulations, smooth particle hydrodynamics, and mesh-free particle techniques with finite element methods. The applications include, cluster impact, penetration phenomena, impact on space shields, space shuttle, explosives, composites, and ceramics. The topics where numerical tools are applied are both diverse and varied and are and indication of an enormously greater level of maturity than what existed a decade ago.

There are novel thrust areas where hypervelocity impact technology is being used to explore material phenomena. Examples include

- radio emissions
- ion formations
- spectral emissions
- plasma formation
- surface modification
- triboro luminescence
- shock-induced vaporization
- phase transitions
- x-ray diffraction

The above list is an indication of researchers' ingenuity in exploring hypervelocity material phenomena where very little is known or established. It is indeed gratifying to note that ingenuity and creativity are alive and well.

CLOSURE

It is encouraging to note that even with the limited funding resources compared to two decades ago, creativity and ingenuity are alive and well. There is considerable overlap in different disciplines that allows researchers to leverage. Experimentally, higher velocities are now available in the laboratory and are ideally suited for space applications that can be tied to both civilian (NASA) and DoD military applications. Computationally, there is considerable advancement both in computer and modeling technologies. Higher computing speeds and techniques such as parallel processing allow system level type applications to be addressed directly today, much in contrast to the situation only a few years ago. Needless to say, both experimentally and computationally, the ultimate utility will depend on the curiosity and the probing questions that will be incumbent upon the individual researcher. It is quite satisfying that over two dozen students attended the symposium. This should provide a good pool of future researchers that will be needed both in the government and civilian industries. It is also gratifying to note that novel thrust areas exploring different and new material phenomenology relevant to hypervelocity impact, but a number of other applications as well, are being pursued.

In summary, HVIS 2005 was a clear success. The Symposium brought together nearly two hundred active researchers and students from thirteen countries around the world. The 84 papers presented at HVIS 2005 constitute an “update” on current research and the state-of-the-art of hypervelocity science. Combined with the over 7000 pages of technical papers from the eight previous Symposia, beginning in 1986, all published in the International Journal of Impact Engineering, the papers from HVIS 2005 add to the growing body of knowledge and the progressing state-of-the-art of hypervelocity science. Thus, considerable progress is still being made for continuing development of hypervelocity science, hypervelocity impact technology and corresponding applications, even with the relatively limited resources that are being directed in this field.

Appendix A
Members of the technical committee for HVIS-2005

Conference Co-Chairmen

Lalit Chhabildas	Sandia National Laboratories
Denny Orphal	International Research Associates

Technical Committee Co-Chairmen

Charlie Anderson	Southwest Research Institute
Stephan Bless	Institute for Advanced Technology
Bill Schonberg	University of Missouri at Rolla

Technical Committee

Tarbay Antoun	Lawrence Livermore National Laboratory
Werner Arnold	EADS-TDW
Ernie Baker	US Army Research and Development Center
Sidney Chocron	Southwest Research Institute
David Crawford	Sandia National Laboratories
Datta Dandekar	Army Research Laboratory
Roberto Destefanis	Alcatel Alenia Space Italia
David Dickinson	Naval Research Center at Dahlgren
Hillary Evans	University of Denver Research Institute
Doug Faux	Lawrence Livermore National Laboratory
Colin Hayhurst	Century Dynamics
Robert Hixson	Los Alamos National Laboratory
Masahide Katayama	CRC Solutions Corp.
Michel Lambert	ESA-ESTEC
Tony McDonnel	UniSpaceKent
Mike Normandia	Cerradyne
K. Poormon	University of Dayton Research Institute
Raj Rajendran	Army Research Office
William Reinhart	Sandia National Laboratories
Sikhanda Satapathy	Institute for Advanced Technology
Martin Sauer	Fraunhofer Institut, EMI
Frank Schafer	Fraunhofer Institut, EMI
Brett Sorensen	Army Research Laboratory
Kazuyoshi Takayama	Tohoku University
Emma Taylor	Open University
Tracy Vogler	Sandia National Laboratories
Joel Williamsen	Institute for Defense Analyses
Leonard Wilson	Naval Research Center at Dahlgren

Appendix B
Meeting Participants for HVIS-2005

Adams	Marc	Jet Propulsion Laboratory
Adlis	David	Aerospace Corp
Ai	Huirong	Caltech
Akahoshi	Yasuhiro	Kyushu Institute of Technology
Alexander	Scott	Sandia National Laboratories
Anderson	Jennifer	Winona State University
Anderson, Jr.	Charles	Southwest Research Institute (SwRI)
Antoun	Tarabay	Lawrence Livermore National Lab
Armstrong	Alan	AFRL/MN
Arnold	Werner	EADS-TDW
Asay	James	Washington State University
Baker	Ernest	US Army RDECOM-ARDEC
Baldwin	Emily	University College London
Banda	Janet	Southwest Research Institute (SwRI)
Barker	Wendy	Valyn VIP
Barker	Zane	Valyn VIP
Barricklow	Shawn	Orbital Sciences Corp.
Baum	Dennis	Lawrence Livermore National Laboratory
Becker	Robert	US Army Space & Missile Defense Command
Behner	Thilo	Fraunhofer Institut EMI
Beissel	Stephen	Army High Performance Computing Research Center
Bergeron	Noah	University of Louisiana at Lafayette
Bettella	Alberto	Cisas-University of Padua-Italy
Bless	Stephan	Institute for Advanced Technology (IAT)
Borg	John	Marquette University
Bradley	Keith	Lawrence Livermore National Laboratory
Bryant	Claude	ESCG/Barrios Technology
Burkett	Michael	Los Alamos National Laboratory
Carrasco	Cesar	FAST Center for Structural Integrity of Aerospace Systems
Cazamias	James	Consultant
Chawla	Monte	Northrop Grumman/Tauri Group
Chhabildas	Lalit	Sandia National Laboratories
Chocron	Sidney	Southwest Research Institute
Christiansen	Eric	NASA Johnson Space Center
Cinnamon	John	USAF Institute of Technology
Clegg	Richard	Century Dynamics Ltd.
Cline	Carl	Advanced Materials Technology International
Compton	Les	Jet Propulsion Laboratory
Corbett	Brooke	University of Denver
Crawford	David	Sandia National Laboratories
Cullis	Ian	QinetiQ
Dandekar	Dattatraya	U.S. Army Research Laboratory
Davis	Bruce	NASA/JSC
Dawson	Anthony	ICES - The University of Texas at Austin
Day	Douglas	AWE PLC
Deeney	Chris	Sandia National Laboratories
Deerman	Brent	Davidson Technologies, Inc.
Destefanis	Roberto	Alcatel Alenia Space Italia
Dickinson	David	Naval Surface Warfare Center
Doney	Robert	U.S. Army Research Lab
Dorsch	Heinrich	IABG VG51

Drury	David	Titan Pulse Sciences
Dukart	Raymond	Sandia National Laboratories
Dutta	Milan	US Army Space & Missile Defense Command
Evans	Hilary	University of Denver Research Institute
Evans	Steven	Marshall Space Flight Center
Fahrenthold	Eric	The University of Texas at Austin
Fair	Harry	Institute for Advanced Technology (IAT)
Faux	Douglas	Lawrence Livermore National Laboratory
Foster	James	SAIC
Fukushige	Shinya	Kyushu Institute of Technology
Galanov	Boris	Institute for Problems of Material Science
Gerber	Bence	Century Dynamics
Gerlach	Charles	Network Computing Services, Inc.
Germann	Timothy	Los Alamos National Laboratory
Gomez	Julian	Auburn University - Space Power Institute
Gooch	William	U.S. Army Research Laboratory Armor Mechanics Branch
Grady	Dennis	Applied Research Associates, Inc.
Green	Mark	AFRL/MNMW
Grove	Brenden	Schlumberger
Hanes	Bruce	Lawrence Livermore National Laboratory
Harano	Takayuki	Kyushu Institute of Technology
Harrison	Wayne	AWE
Harvey	William	Baker Hughes/Baker Atlas
Hayhurst	Colin	Open University
Henderson	Don	Honeywell
Hertel	Eugene	Sandia National Laboratories
Hideaki	Kusano	Shimadzu Corporation
Higashide	Masumi	Kyushu Institute of Technology
Hixson	Robert	Los Alamos National Laboratory
Hlady	Sheri	DRDC Suffield
Hohler	Volker	Fraunhofer Institut EMI
Holmquist	Tim	Network Computing Service
Hopson	Michael	Naval Surface Warfare Center Dahlgren Division
Hornung	Klaus	Universität der Bundeswehr
Hsiung	Luke	Lawrence Livermore National Laboratory
Hyde	Jim	NASA/JSC
Imai	Hiroshi	Shimadzu Corporation
Johnson	Gordon	Network Computing Services, Inc.
Juthani	Nimesh	The COOKE Corporation
Kalantar	Daniel	Lawrence Livermore National Laboratory
Kartuzov	Valeriy	IPMS
Kartuzov	Igor	IPMS
Kashine	Ganjiro	SANPO PUBLICATION
Katayama	Masahide	CRC Solutions Corp.
Katz	Sari	Soreq, NRC
Kaufman	Todd	Honeywell
Kelly	Dan	Sandia National Laboratories
Knudson	Marcus	Sandia National Laboratories
Kosel	Frank	DRS Technologies
Lambert	Michel	ESA-ESTEC
Laurence	Peter	Titan Pulse Sciences
Lawrence	R. Jeffrey	Sandia National Laboratories
Lee	Minhyung	Sejong University
Lewis	Keith	NSWC - Dahlgren Division
Lianos	Pete	Radiance Technologies, Inc.
Limlamai	Manit	Lockheed Martin Space Systems Co.

Littlefield	David	University of Alabama at Birmingham
Lloyd	Andrew	Consultant
Lomonosov	Igor	Institute of Problems Chemical Physics
Lucero	Amy	Sandia National Laboratories
Lynch	Nicholas	QinetiQ
Manning	Heidi	Concordia College
McDonnell	J.A.M.	UniSpaceKent
Mellado	Eva Maria	Federal Armed Forces University Munich
Michel	Yann	Ensica
Milner	Daniel	University of Kent
Monaco	Janet	Institute for Advanced Technology (IAT)
Morris	Joseph	Lawrence Livermore National Laboratory
Mullin	Scott	Southwest Research Institute (SwRI)
Nechitailo	Nicholas	Naval Surface Warfare Center
Nicolich	Mark	U.S. Army ARDEDC
Nishida	Masahiro	Nagoya Institute of Technology
Normandia	Michael	Cerradyne, Inc.
Ohtani	Kiyonobu	IFS, Tohoku University
Olsen	Greg	Mississippi State University
Orphal	Dennis	International Research Associates
Piekutowski	Andrew	University of Dayton Research Institute
Pilz	Steve	ANSYS, Inc.
Poe	Kenneth	Naval Surface Warfare Center
Poormon	Kevin	University of Dayton Research Institute
Pope	Matthew	AFRL
Povarnitsyn	Mikhail	Institute for High Energy Density RAS
President	Ashley	Raytheon
Quan	Chris	Century Dynamics
Quinn	Catherine	NSWC-Dahlgren
Rabb	Robert	University of Texas at Austin
Rager	Audrey	University of Nevada, Las Vegas
Rae	Cheryl	Institute for Advanced Technology (IAT)
Ramsey	Michelle	Institute for Advanced Technology (IAT)
Reimerdes	Hans-G	Institut fur Leichtbau
Reinhart	William	Sandia National Laboratories
Remelman	Mark	Spectral Dynamics, Inc.
Rhodes	Justin	US Army RDECOM
Riedel	Werner	Fraunhofer Institut EMI
Riha	David	Southwest Research Institute
Rodriguez	Karen	NASA JSC - White Sands Test Facility
Rönn	Torsten	BAE Systems
Royer	Dave	Space Research Institute
Rumbaugh	Todd	DRS Data & Imaging Systems
Ryan	Shannon	Fraunhofer Institute EMI
Sadrai	Sepehr	University of British Columbia (UBC)
Saito	Tsutomu	Muroran Institute of Technology
Satapathy	Sikhanda	Institute for Advanced Technology (IAT)
Sauer	Martin	Fraunhofer Institut EMI
Schaefer	Frank	Fraunhofer-Institut fürKurzzeitdynamik
Schirm	Volker	French German Research Institute
Schneider	Eberhard	Fraunhofer Institut EMI
Schonberg	William	University of Missouri
Schultz	Peter	Brown University
Sheffield	Stephen	Los Alamos National Laboratory
Shockey	Donald	SRI International
Silverblatt	Bryan	NAV EOD TECH DIV

Smith	Patti	Oxford Lasers
Smith	Meagan	Oxford Lasers
Sorensen	Brett	U.S. Army Research Laboratory
Springer	Keo	Lawrence Livermore National Laboratory
Stallworth	Roderick	NASA/Marshall Space Flight Center
Tadaoka	Masayoshi	Kyushu Institute of Technology
Takayama	Kazuyoshi	Shock Wave Research Center - Tohoku University
Tamminga	Josh	Honeywell
Tanaka	Koichi	Nagoya Institute of Technology
Taylor	Emma	Open University
Templeton	Doug	U.S. Army TARDEC-TACOM
Thoma	Klaus	Fraunhofer Institut fur Kurzzeitdynamik
Thornhill	Tom	KTech Corp
Tipton	John	US Army Space & Missile Defense Command
Verker	Ronen	Soreq NRC
Vial	Gilbert	Shimadzu Scientific Instruments, Inc.
Vogler	Tracy	Sandia National Laboratories
Vulitsky	Mark	Titan
Walker	James	Southwest Research Institute (SwRI)
Walters	William	U.S. Army Research Laboratory ARL-WMRD
Watanabe	Keiko	Kyushu Institute of Technology
Wei	Zhigang	The University of Texas at Austin
Weir	Robert	Sandia National Labs
Welch	George	US Army Space & Missile Defense Command
Wells	Brian	Auburn University
Wilbeck	James	ITT Industries, AES
Williamsen	Joel	Institute for Defense Analyses
Wilson	Leonard	Naval Surface Warfare Center
Zhang	J. Jay	Corning Incorporated
Zhou	Jikou	Lawrence Livermore National Laboratory
Zhou	Fenghua	Johns Hopkins University
Zwissler	James	Jet Propulsion Laboratory

Appendix C

The following are the titles and authors of all the papers presented at the HVIS 2005, arranged by topic area. The Proceedings of the Symposium will be published as a special volume of the International Journal of Impact Engineering.

Launchers and Diagnostics

1. **New Ideas in Piezoelectric Ejecta Diagnostics for Shock-Loaded Environments**- *W.S. Vogan, W.W. Anderson, M. Grover, R.S. Hixson, N.S. P. King, S.K. Lamoreaux, G. Macrum, K.B. Morley, P. Rigg, G. Stevens, W.D. Turley, L. Veeser, W.T. Buttler,* Los Alamos National Laboratory, USA

2. **Development of Perforation Hole Detection System for Space Debris Impact**- *S. Fukushige, Y. Akahoshi, T. Koura, and S. Harada,* Kyushu Institute of Technology, Japan

3. **The Open University New "baby" Gun: A Compact 2 Stage Light Gas Gun for All Impact Angles**- *J.A.M. McDonnell,* Open University and UnispaceKent, United Kingdom

4. **An Upgraded High-Velocity Dust Particle Accelerator at Concordia College in Moorhead, Minnesota**- *H.L.K. Manning, J. Gregorie,* Concordia College, USA

5. **Particle Launch to 19 km/s for Micro-Meteoroid Simulation Using Enhanced Three-Stage Light Gas Gun Hypervelocity Launcher Techniques**- *T.F. Thornhill, W.D. Reinhart, and L.C. Chhabildas,* Sandia National Laboratories, USA

6. **Development of a Three-Stage, Light-Gas Gun at The University of Dayton Research Institute**- *A.J. Piekutowski and K.L. Poormon,* University of Dayton Research Institute, USA

7. **Preliminary Study of Counter Impact with Two-Stage Light Gas Gun Using Electrothermal-Chemical Gun Technology**- *Y. Akahoshi, M. Tadaoka, T. Koura, S. Fukushige, E. Matuda, J. Kitagawa, Q. Yanzhe,* Kyushu Institute of Technology, Japan

8. **Cryogenic and Elevated Temperature Hypervelocity Impact Facility**- *B. Wells,* Auburn University, USA

9. **Critical Velocity for Rails in Hypervelocity Launchers**- *N.V. Nechitailo and K.B. Lewis,* Naval Surface Warfare Center, USA

10. **Active Piston Technique to Optimize Muzzle Pressure in Two-Stage Light-Gas Guns**- *D.Pavarin and A. Francesconi,* CISAS University of Padova , Italy

11. **The Design and Flight Performance of Advanced Carrier Projectiles at Hypervelocity**- *I G Cullis, D Jenner, I Huggett, and N Lynch,* QinetiQ, United Kingdom

12. **Structure of a Shaped Jet Formed in an Oblique Collision of Flat Plates**- *O.B. Drennov,* VNIIEF, RFNC , Russia

Impact and Penetration

13. **Hypervelocity Penetration of Gold Rods into SiC-N for Impact Velocities from 2.0 to 6.2 km/s** - *T. Behner, D.L. Orphal, V. Hohler, C.E. Anderson, Jr., R. Mason, and D.W. Templeton,* Ernst Mach Institute, Germany

14. **The Dependence of Penetration Velocity on Impact Velocity**- *D.L. Orphal and C.E. Anderson, Jr.,* International Research Associates, USA

15. **Re-examination of the Evidence for a Failure Wave in SiC Penetration Experiments**- *C.E. Anderson, Jr., D.L. Orphal, T. Behner, V. Hohler, and D.W. Templeton,* Southwest Research Institute (SwRI), USA

16. **Impact Behaviour of PELE Projectiles Perforating Thin Target Plates** - *G. Paulus and V. Schirm,* French-German Research Institute of Saint-Louis ISL, France

17. **The Influence of Confinement on the Penetration of Ceramic Targets by KE Projectiles at 1.8 and 2.6 KM/S**- *N.J. Lynch, S. J. Bless, I.G. Cullis, and D.T. Berry,* QinetiQ, United Kingdom

18. **Damage-Potential Comparison of Spherical and Cylindrical Projectiles Impacting on a System of Bumper Plates**- *C. Carrasco, O. Melchor-Lucero, R. Osegueda, L. Espino, and A. Fernandez,* FAST Center for Structural Integrity of Aerospace Systems, USA

19. **Lateral Confinement Effects in Long-Rod Penetration of Ceramics at Hypervelocity**- *I.S. Chocron, C.E. Anderson, Jr., Th. Behner, and V. Hohler,* Southwest Research Institute, USA

20. **Simulation of Hypervelocity Penetration in Limestone**- *T. H. Antoun, O. Walton, P. Goldstein, I. N. Lomov, and L. Glenn,* Lawrence Livermore National Lab, USA

21. **An Explicit Solution of the Alekshevskii-Tate Penetration Equations** - *W. Walters and C. Williams,* U.S Army Research Laboratory, USA

22. **Protection Effectiveness of an Oblique Plate Against a Long Rod** - *Y. H. Yoo and M. Lee,* Sejong University, Korea

23. **Penetration of Boron Carbide, Aluminum, and Beryllium Alloys by Depleted Uranium Rods: Modeling and Experimentation**- *J. D. Walker, S. A. Mullin, C. E. Weiss, and P. O. Leslie,* Southwest Research Institute (SwRI), USA

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