## Los Alamos National Laboratory (LANL)
## Current Projects with the Russian Federation

**Computational Project Title:** "Study and Implementation of Multi-Material Pressure Relaxation Methods for Lagrangian Hydrodynamics and Arbitrary Lagrangian-Eulerian Hydrodynamics"(TO 039)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Description:** The numerical simulation of multi-material compressible flows presents numerous modeling challenges. In particular, there are several competing approaches with which to model multi-material cells in the Lagrangian frame under the assumption of pressure relaxation with a single velocity. The main challenge is to accurately assign the thermodynamic states of the individual material components, despite a lack of detailed information about the velocity distribution within such multi-material cells. The relations among these different approaches remain largely unexplored. It is anticipated that a deeper understanding of these models will lead to new algorithms that are both more accurate and more robust than existing numerical schemes. This activity involves the clear motivation, thorough description, and quantitative evaluation of algorithms for modeling one-dimensional, multi-material, compressible flows in the Lagrangian frame. The quantitative comparison of these algorithms on well-codified test problems forms the rigorous basis by which to evaluate these models.

**Publications:**

Yu. Yanilkin, E. Goncharov, V. Kolobyanin, V. Sadchikov, J. Kamm, W. Rider and M. Shashkov.
"Some Multi-Material Closure Models for 1-D Lagrangian Hydrodynamics", SAND2011-6003C. – Presentations at MULTIMAT 2011 Conference, Arcachon, France - http://multimat2011.celia.u-bordeaux1.fr/.

Yu. Yanilkin, E. Goncharov, V. Kolobyanin, V. Sadchikov, J. Kamm, W. Rider and M. Shashkov. "Multi-material Pressure Relaxation Methods fro Lagrangian

Hydrodynamics", LAUR-12-00056, Accepted for publication at Journal of Computer and Fluids.
J. Kamm, M. Shashkov, J. Fung, A. Harrison and T. Canfield. "A comparative study of various pressure relaxation closure models for one-dimensional two-material Lagrangian Hydrodynamics", Int. J. Num. Meth. Fluids, v. 65, n. 11-12, pp. 131-1324.
A. Harrison, M. Shashkov, J. Fung, J. Kamm and T. Canfield. " Development of a sub-scale model for pressure relaxation of multi-material cells in Lagrangian hydrodynamics", J. EPJ Web Conferennces, 2100014X, 2011, v.10, 00039.
J. Kamm, M. Shashkov and W. Rider. "A new pressure relaxation closure model for one-dimensional two-material Lagrangian hydrodynamics", J. EPJ Web Conferennces, 2100014X, 2011, v.10, 00038.

**Project Principal Investigators:** M. Shashkov, (LANL).
Yu.V. Yanilkin, (VNIIEF).

**Dynamic Materials Project Title:** Understanding the Phase Changing Materials Titanium and Cerium (TO 40)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Description:** This multi-year project builds upon knowledge obtained from former task orders and will examine the phase-changing materials of cerium and titanium. In a former task order, namely TO 035 (Shock compression studies of phase-changing materials with PVDF and Manganin gauges), cerium samples were destroyed with a smooth spalled layer. This process took place at aluminum impactor velocities of approximately 200 m/s. This series of experiments will be supplemented by pre-experiment and post-experiment metallographic analysis. The samples will be recovered and metallographically analyzed. The metallographic analysis should provide insight into the mechanisms of porosity and crack formation, spallation, fracture, and phase transformation.

In conjunction with the metallographic analysis, the shock wave loading structure will be recorded. A detailed analysis of the shock wave fronts will yield sound velocities for the higher pressure phases and Hugoniot data. For cerium Hugoniot data will be obtained in pressures less than 10 GPa where only a few Hugoniot data points to date. In the case of titanium the pressure range will be between 5 and 30 GPa that are below the melt pressures of titanium.

**Current Status:** This Task Order ended in FY11. Follow-on work is expected to continue under a new task order.

**Project Principal Investigators:** F.J. Cherne , (LANL).
M.V. Zhernokletov , (VNIIEF).

**Dynamic Materials Project Title:** Studies of Constitutive Behavior and Damage Mechanics (TO 44)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Description:** The formulation of mathematical models capable of predicting the behavior of materials when subjected to some given thermo-mechanical loading environment is an area of active research. Included in this research are models for predicting the constitutive response of the material, and the initiation and evolution of damage. Successful development of such predictive models inherently relies on experimental data obtained from laboratory tests carefully constructed to evaluate some particular thermo-mechanical response or mechanism. These experimental results then support the development of theoretical models, which can be implemented into a variety of numerical methods, thereby providing general-purpose predictive tools.

A variety of experimental techniques will be used in support of this work: e.g., split Hopkinson pressure bar (SHPB), Taylor cylinder, flyer plate impact, quasi-isentropic and shock loading by the expansion of HE detonation products.

Multiple materials will be studied: copper, tantalum, and possible other (yet to be determined) material(s). Issues likely to be investigated include, but are not limited to, the effect of grain size on constitutive behavior and the mechanics of damage: the effect of deformation localization on constitutive behavior and the mechanics of damage: the evolutionary processes involved in both the time and spatial dependence of grain morphology and deformation localization: time-scale effects related to transient thermal softening associated with deformation localization—both as it affects constitutive behavior and as it affects damage initiation and evolution; the mechanisms involved in damage compaction and the apparent ”healing” of previously damaged materials; the effects of such “healing” on subsequent constitutive behavior and sequel damage evolution; the convergence of cylindrical channels

under shock loading; and the influence of a time factor associated with the formation of heterogeneous structures on damage nucleation.

Experiments will be conducted in support of model development and validation. Metallographic analysis will be used to assess micro-structural morphologies. Existing material models will likely be improved. It is possible that entirely new material models will be developed. Extensive numerical analysis will be conducted to assess the validity of numerical models.

**Current Status:** This is follow-on to now completed Task Order 021. This Task Order will transition to a new agreement replacing Agreement 37713, expiring in mid FY12.

**Project Principal Investigators:** M.A. Zocher, D.L. Preston , (LANL).
O.N. Ignatova, (VNIIEF).

**Dynamic Materials Project Title:** The Development of Mathematically Exact Solutions for Shell Structures as Benchmark Solutions for Large Computational Analysis Codes (TO 45)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Description:** Exact solutions to the governing differential equations for shell structures are important benchmark solutions for verifying the accuracy of large computational analysis codes. Thus, the development of such solutions represents an important area of research as large computational analysis codes play an integral role in fulfilling LANL's core mission.

The formulation of mathematically exact solutions for the response of shell structures when subjected to different thermo-mechanical loading states is an area of active research. Current work at LANL has developed solutions for the geometrically linear and nonlinear elastic behavior of shell structures as well as the geometrically linear, history-dependent behavior of such structures for spherically symmetric loading states.

Collaborations between LANL and VNIIEF pursuing the development of extensions of the existing solutions are proposed. Possible extensions include the development of thermo-mechanically coupled physics, i.e., solving both the equations of motion and the energy equation simultaneously, as well as incorporating equation-of-state (EOS) behaviors into the analysis. Other extensions will also be considered.

**Current Status:** Task Order expected was placed in FY11 and will conclude in mid FY13.

**Project Principal Investigators:** T.O. Williams, J.S. Brock, M.A. Zocher , (LANL).
S.S. Sokolov, (VNIIEF).

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| **Materials Project Title:** | Phase Transition Kinetics and Constitutive Response of Pure Cerium (TO 010) |
| **Russian Institute:** | Russian Federal Nuclear Center—All-Russian Scientific Research Institute of Technical Physics (RFNC-VNIITF) |
| **Brief Description:** | Under a previous task order, VNIITF conducted an extensive suite of experiments to measure the time-resolved kinetics of the α-ε phase transition in pure iron and 30 CGSA steel, and to investigate the influence of the phase transformation on the spallation behavior. In this project, planned for ten years (FY04-FY13) we will extend this work to a metal with a more complex dynamic response, namely cerium. The effects of shock-induced solid-solid and melting phase transitions on the high-rate stress-strain response of pure cerium will be investigated by mean of Hopkinson bar tests. Phase transformation kinetics will be measured in numerous wedge experiments utilizing the optical lever technique. VNIITF will attempt to carry out several additional wedge experiments with sample recovery for metallographic analysis. Several planar shock wave experiments will be conducted to measure stress wave profiles (kinetics) and sound velocities in shock-compressed Ce, and to determine where Ce melts on the shock Hugoniot. VNIITF will construct a preliminary multi-phase equation-of-state (EOS) for Ce, and Los Alamos and VNIITF modelers will jointly develop a theoretical description of the phase transformation kinetics and a preliminary deviatoric constitutive model for Ce. We expect to collaborate on research into the spall process in the future. |
| **Current Status:** | Mod 6 has been released. This Mod introduces new deliverable 5.3.4 and defines the remaining work for the FY11-FY15 time frame. Specimens were shipped to VNIITF in 2011. |
| **Project Principal Investigators**: | D.L. Preston, M.A. Zocher, Gray, G.T., III, F.J. Cherne (LANL).<br>A.V. Petrovtsev (VNIITF). |

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| **Materials Project Title:** | Molecular Dynamics Studies of Pu Aging (TO 14) |
| **Russian Institute:** | Russian Federal Nuclear Center—All-Russian Scientific Research Institute of Technical Physics (RFNC-VNIITF) |
| **Brief Description:** | The development of physically based models of material properties evolution in time due to self-irradiation requires, in general, an understanding of physical mechanisms at micro-scales level. The only technique for direct theoretical investigation into the processes and their effect upon macroscopic properties of the material is molecular dynamics simulation. We suggest continuing MD investigation into the mechanisms of defects and products of decay accumulation in plutonium due to self-irradiation. Preliminary model of point-like defects accumulation and saturation in single-crystal has been constructed during the final stage of the Task Order 009 on the basis of MD simulation of damage region annealing and calculation of point-like defects mobility. The effect of the accumulation on the thermodynamic and mechanical properties was evaluated in comparison of perfect and defect crystals. Now the model should be added with grain boundaries effects. After that one will be able to make conclusion about the role of point-like defects in Pu properties evolution in time. There are two more factors affecting Pu properties – products of decay and metastability of fcc phase. Evaluation of their effect upon mechanical properties is the goal of the project. |
| **Current Status:** | This project is scheduled to end with the conclusion of mid-FY13. |
| **Project Principal Investigators:** | D.L. Preston, M.A. Zocher, T.C. Germann (LANL).<br>V.V. Dremov (VNIITF). |

**Materials Project Title:** Calculations of the Properties of the Alpha, Gamma, and Epsilon Phases of Cerium using the LDA+DMFT Method (TO 16)

**Russian Institutes:** Russian Federal Nuclear Center—All-Russian Scientific Research Institute of Technical Physics (RFNC-VNIITF)
**And**
Institute of Metal Physics (IMP)

**Brief Description:** The development of methods for calculating the properties of strongly correlated electron systems is currently an area of very active research. In strongly correlated materials the electrons occupy incompletely filled 3d (transition metals), 4f (lanthanides), or 5f (actinides) orbitals. Such materials, for example cerium and plutonium, have electronic structures that are neither ionic nor free-electron-like, but a mixture of both. There is competition between delocalization, leading to band formation, and a tendency toward localization and atomic-like behavior. Density functional theory (DFT), which is a very successful ab initio approach for predicting the ground-state properties of weakly correlated solid state systems, metals in particular, fails in strongly correlated materials. The strong correlations preclude a description in terms of well-defined quasi particles; hence, band structure methods are not sufficient and a genuine many-body approach is necessary. One of the most successful approaches for incorporating many-body physics is the powerful but practical dynamical mean field theory (DMFT), in which the solid-state many-body problem is mapped onto a quantum impurity model. Recently, DMFT was combined with LDA (local density approximation) (Anisimov, Poteryaev, Korotin, Anokhin, and Kotliar). This LDA+DMFT approach combines the advantages of LDA, a successful method in the weak-correlation limit, with a correct description of the correlations within DMFT.

In the first year LDA+DMFT will be used to calculate the spectral and magnetic properties of cerium to validate the method. The relative stabilities of the $\alpha$, $\gamma$, and $\varepsilon$ phases of cerium will be determined in the second year by calculating the total energy as a function of volume at zero temperature. In the third year a method for calculating interatomic forces will be developed. This is an essential

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| | step toward our long-term goal of writing a molecular dynamics code based on LDA+DMFT. |
| **Current Status:** | This project will continue through FY14. |
| **Project Principal Investigators:** | D.L. Preston, M.A. Zocher (LANL).<br>V.V. Dremov (VNIITF). |

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| **Materials Project Title:** | Study of Mesodefect Induced Mechanisms of Thermally Activated Plastic Flow and Transition to Overdriven Shock (TO 12) |
| **Russian Institutes:** | Sarov Labs<br>AND<br>Institute of Continuous Media Mechanics, Russian Academy of Sciences (RAS) |
| **Brief Description:** | Considerable uncertainty currently exists regarding the fundamental physical mechanisms responsible for material behavior during the transition from thermally activated plastic flow to overdriven shock. Current models (such as PTW) attempt to predict the behavior phenomenologically, with little or no accounting of the underlying physical processes. The objective of the proposed work is to gain a better understanding of the underlying physical processes at play in the transition region, and to develop a model that accounts for these processes. Such a model may prove to be superior to current models, especially when the fundamental mechanisms involved in material flow change within the transition zone. Recent experimental data suggests that this issue may be. |
| **Current Status:** | This project will continue through FY13 |
| **Project Principal Investigators:** | M.A. Zocher, D.L. Preston, (LANL).<br>Oleg Naimark, Institute of Continuous Media Mechanics, Russian Academy of Sciences (RAS). |

**Pulsed Power Hydrodynamics**

**Project Title:** Advanced Liner Technology using VNIIEF Disk Explosive Magnetic Generators (DEMG) (TO 010)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Project Description:** The objective of this project is to make Russian DEMG technology available for use in Science Campaign #1 experiments potentially including experiments conducted in the U.S. Because of the substantial investment that VNIIEF has made in developing this technology, VNIIEF agreed in 2004 to enter into a joint development effort with LANL to design new, or modified DEMG system(s) to meet specific technical needs instead of licensing the technology to LANL.

Export control issues, beyond the immediate control of VNIIEF, may add complexity or extend the time scale for completing this subtask or make it impossible to complete this effort. Because a relatively complete description, "design", is required before the export control issues can be fully explored in Russia, this subtask will pursue the work through design and initial testing in VNIIEF. The export issues will be evaluated when appropriate.

A DEMG capability may be needed in the U.S. for LANL experiments after FY14 to support Science Campaign 1 pulsed power hydrodynamics experiments that cannot be conducted on existing U.S. facilities and that cannot be conducted in VNIIEF.

The new DEMG extends implosion parameters accessible by magnetically driven condensed matter implosion to higher energy and velocity. A very-high pressure equation-of-state (EOS) experiment is the initial design objective for this subtask, but the system issues are common to virtually any liner driven experiment. For example ,the Damaged Surface Hydrodynamics series challenges existing simulation capability (behavior of fluid-like – or particle-like – damaged layers in implosion geometry) to evaluate

current models and motivate development of new ones as appropriate. Alternatively, a warm-dense matter experiment provides data to add to the very sparse family of experimental data in the regime 10% to 3X of normal density and 1-50 eV.

**Current Status:**

This is a multi-year effort that was planned in eight phases starting in FY03. Conceptual design reports were delivered in 2003 and 2004. The first prototype generator hardware was produced in late 2009 and 2010. Subsystem tests are continuing in 2012. Detailed design calculations continue in both VNIIEF and LANL with the first full-scale test (ALT-3) scheduled for autumn 2013.

**Publications:**

A.M.Buyko, O.M.Burenkov, V.V Zmushko et al. “On the feasibility to achieve high pressures with disk EMG driven impacting liners” Digest of Technical Papers, PPPS-2001, 2001. P. 516-519.

A.M.Buyko, Yu.N.Gorbachev, V.V.Zmushko et al. “Simulation of Atlas parameters in explosive magnetic experiments ALT-1,2”, Proc. of 9th Int. Conf. on Megagauss Magn. Field Generation and Related Topics. Moscow – St.Petersburg, 2002, Sarov, VNIIEF, 2004. P. 747-751.

A.M.Buyko, S.F.Garanin, A.I.Glybin et al. “A Disk EMG System for Driving Impacting Liners to ~20km/s” Proc. Int.Conf. XIII Khariton Scientific Talks "Extreme States of Matter. Detonation. Shock Waves.” RFNC-VNIIEF, Sarov, 2011. P. 488-495.

A.M.Buyko, S.F.Garanin , V.V.Zmushko et al. “Simulations of Magnetic Implosion of Impacting Liners Driven to ~20km/s Proc. Int.Conf. XIII Khariton Scientific Talks "Extreme States of Matter, Detonation, Shock Waves.” RFNC-VNIIEF, Sarov , 2011. P. 549-556.

A.M.Buyko, S.F.Garanin, V.V.Zmushko et al. “Simulations of high-velocity condensed liner magnetic implosion for experiments with disc EMGs”, Int. Conference MG-12, Novosibirsk, 2008.

A.G.Sgro, W.L.Atchison. “Simulation of Magnetically Driven Experiments” Proc. XIII Khariton Scientific Talks "Extreme States of Matter. Detonation. Shock Waves.”

RFNC-VNIIEF, Sarov , 2011. P. 211-221.
A.M.Buyko, S.F.Garanin, D.V.Karmishin et al. “Analysis of the Liner Stability in Various Experiments” IEEE Transactions on PLASMA SCIENCE, Vol. 36, Issue 1, 2008. P. 4-9.
I.D.Sofronov, O.A.Vinokurov, V.V. Zmushko et al. MIMOZA Code. “Multidimensional Hydrodynamic Simulations” Mathematical Modeling Issues in Computational Mathematics and Informatics. Scientific Transactions. Moscow - Arzamas-16, 1994.
A.M.Buyko, S.F.Garanin, V.V.Zmushko et al. “2D computations for perturbation growth of magnetically driven cylindrical aluminum and aluminum alloy liners” Proceedings of the 7th International Workshop on The Physics of Compressible Turbulent Mixing, St.Petersburg, 1999, Yu.Yanilkin & V.Zhmailo, Sarov, Russia, 2001. P. 237-243.
A.M.Buyko, A.G.Ivanov, Yu.D.Lavrovsky et al. “Formation of Jets During High-Velocity Impact of a Thin Shell on Various Targets” Int.Conf. IV Zababakhin Scientific Talks, Snezhinsk, Chelyabinsk reg., Russia, 1995. P. 164-171.

**Project Principal Investigators:** R.E. Reinovsky, C.R. Rousculp, (LANL).
A.N Buyko, A. Ivanovsky, A. Kraev, (VNIIEF).

**Pulsed Power Hydrodynamics**

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| **Project Title:** | Exploration of Damage Mechanisms in Cylindrical Geometry (TO 024) |
| **Russian Institute:** | Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF) |
| **Brief Project Description:** | The objective of this effort is to obtain damage data in (presumably well) understood materials for comparison with (and validation of) current models of damage processes and to motivate the development of new models suitable for use in new computational tools being developed in the Advanced Simulation and Computing (ASC) Program. Specific objectives include obtaining well-characterized experimental data near failure threshold and in regimes where reacceleration of the native material leads to void closure after damage.<br><br>Development of models of the behavior of damage mechanisms in metals in complex stress states and experimental validation of those models over a wide range of conditions is important for ASC including full-scale simulations of complex implosion experiments conducted with detailed diagnostics in spatial and temporal conditions comparable to those encountered ASC problems. A convergent geometry allows access to non-one-dimensional stress states and offers the possibility of exploring void closure behavior as the native material behind the damaged region accelerates in the later stages of the cylindrical implosion. Magnetically driven implosions provide a degree of controllability and precision not available with other cylindrical implosion techniques. These experiments provide data in a convergent geometry that overlaps with, and extends, planar gas-gun damage data. Both LANL and VNIIEF will collaborate in data analysis and may contribute failure models for development and validation. |
| **Current Status:** | A series of ten experiments was completed in Sept 2011; dual language final technical reports are planned for 2012. |

**Publications:**

A. M. Kaul "An experimental series to study spallation damage in cylindrical geometry" Khariton Topical Readings "Extreme States of Substance; Detonation; Shock Waves" Sarov, Russia, 14 – 18 March, 2005.

P.V. Duday, A.M. Glybin, V.A. Ivanov et al. Quasi-trapezoidal shape current pulse former. Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, November 5-10, 2006, Santa Fe, New Mexico, USA.

V.K. Chernyshev, G.I. Volkov, V.A. Ivanov et al. Explosive Opening Switches for Fast-Operating Helical EMG // Proc. Ninth IEEE Pulsed Power Conference, 1993, Albuquerque, New Mexico, USA.

A.A.Zimenkov, P.V.Duday, S.V.Pak, A.N.Skobelev. Helical EMG designing with the use of a computer calculation program. Proceedings "XIII Khariton Topical Readings on the problems of high energy density physics", Sarov, Russia, 19 – 23 April, 2010.

P.V.Duday, V.A.Ivanov, A.V.Ivanovsky, A.I.Kraev, V.B.Kudelkin, A.I.Kuzayev, A.A.Petrukhin, A.N.Skobelev, B.G. Anderson, W.L. Atchison, A.M. Kaul, M. Salazar, G. Rodriguez, R.E. Reinovsky, L. Tabaka, D.T. Westley et al. Experimental test bench on the basis of a helical EMG to study spallation mechanisms in cylindrical geometry. Proceedings "VII Khariton Topical Readings on the problems of high energy density physics", Sarov, 21 – 24 March, 2006.

D. L. Tonks, et al. "Spallation Modeling Using Experiments on the Atlas Pulsed Power Machine," Khimicheskaya Fizika **10** 93-103 (2005).

**Project Principal Investigators:**

A. Kaul W.L. Atchison, (LANL).
A. Buyko, A. Ivanovsky, P Duday, (VNIIEF).

**Pulsed Power Hydrodynamics**

**Project Title:** Warm Dense Matter and the MHD Behavior of Conductors in Ultra High Magnetic Fields (TO 037)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Project Description:** Understanding the interaction of very intense magnetic fields (B>100T) with a metal conductor is fundamental to assessing the limits to which condensed matter liners can be accelerated for use in experiments supporting NNSA Science Campaign #1. Garanin at Sarov has revisited this relatively traditional problem, exploring the behavior of the vapor/plasma created on a surface when the current density is high enough to produce magnetic field > 100 T and has found some important deviations from traditional results when electron thermal conduction and radiation transport in the vapor/plasma is considered. If Garanin's theoretical and simulation results are validated by experiments, new insight into the limits of useful liner behavior may emerge.

The University of Nevada, Reno (UNR) began a program in FY06 to produce experimental data, funded by the DOE Office of Science, using the Nevada Terrawatt Facility (NTF) in Reno coupled with modern diagnostic techniques to characterize the behavior of a metal surface at ultra intense fields for comparison with Garanin's analysis. While aspects of the plasma/ field/ wall interaction have been explored, largely anecdotally, over the last several decades, a controlled, carefully diagnosed data set obtained at values of the magnetic field where the complex processes actually interact has not been produced. The advent of modern (especially microsecond time-scale) pulsed power machines makes it practical, and quite economical, to produce such a definitive data set at this time.

In the course of developing the experiment to examine the surface plasma, it was found that, at NTF parameters and at times later than those relevant to the surface plasma formation, the underlying material settled into a stable

column at densities about 60% of solid density and several eV temperature – a distinctly in the hard to access transitional regime between plasma and condensed matter called "warm-dense matter." Because of the fundamental importance of this regime to Science Campaign #1, this effort was expanded to include theoretical, simulation (and possibly experimental) work to characterize equation-of-state (EOS) and transport properties of this regime.

This task order engages the Garanin theoretical team in the planning, conduct, and analysis of the data from the experiments planned by UNR at the NTF. This approach opens a new chapter in the LANL/VNIIEF collaboration in which the technical expertise of a University program is combined with LANL expertise and mission needs and with VNIIEF capability to address a scientifically challenging and programmatically relevant problem.

**Current Status:**

The UNR program has conducted several series of experiments at the NTF sponsored by DOE-OFES. Data from the Reno experiments has been forwarded to VNIIEF for their analysis. A workshop was conducted at Reno in April 2008 on the "Computational Modeling of the UNR Megagauss Experiment that included personnel from VNIIEF, LANL and Reno, and contributions from interested researchers in AFRL, Sandia and Numerex (a private sector contractor). Results from the experiment were presented at the Megagauss 2008 Conference in Novosibirsk in July 2008 by the UNR graduate student conducting the experiment and discussed at length with VNIIEF at the conference. LANL has fabricated experimental samples for the next series of experiments at Reno, and LANL personnel continue to conduct simulations. The first deliverable, VNIIEF independent analysis of the Reno data was delivered in FY09, and a second informal workshop involving UNR, LANL, VNIIEF, University of Texas, Sandia, AFRL and private industry was conducted in Albuquerque in Sept 2009.

The second objective for this task order, is a study directed toward exploration of the warm-dense matter conditions

present in the UNR experiment at late time began in FY10 and continues. Initial results of the study were presented in the Barcelona Conference in October 2011 and will be discussed for the general community in the Megagauss Conference in October 2012.

**Follow-on Activities:**

An experiment at VNIIEF using DEMG's or other current source to explore fields higher than those available at the NTF, and on samples larger than those that can be driven on the NTF will be considered.

**Publications:**


S. F. Garanin, "Diffusion of a strong magnetic field in a dense plasma," *J. Appl. Mech. Tech. Phys.*, No. 3, 308-312 (1985).

S. F. Garanin, "Discharge arising at magnetic flux outflow from plasma to insulator" (in Russian), *PMTF* (*J. Appl. Mech. Tech. Phys.*), No. 6, 13-16 (1987).

S. F. Garanin and V. I. Mamyshev, "Cooling of a magnetized plasma at a boundary with an exploding metal wall," *J. Appl. Mech. Tech. Phys.*, No. 1, 28-34 (1990).

S. F. Garanin, G. G. Ivanova, D. V. Karmishin, and V. N. Sofronov, "Diffusion of a megagauss field into a metal," *J. Appl. Mech. Tech. Phys.*, Vol. 46, 153-159 (2005).

S. F. Garanin and D. V. Karmishin, "Stationary discharge sustained by electron thermal conduction for emergence of a magnetic flux through an insulator surface," *J. Appl. Mech. Tech. Phys.*, Vol. 45, 639-646 (2004).


**Project Principal Investigators:**

R. E. Reinovsky, (LANL).
Prof. Richard Siemon, (UNR).
Sergey Garanin, (VNIIEF).

**Pulsed Power Hydrodynamics**

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| **Project Title:** | Modeling of Explosive Opening Switch and Potential Extension of Switch Performance (TO 043) |
| **Russian Institute**: | Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF) |
| **Brief Project Description:** | Explosive driven current interrupting switches are a key element in US and Russian HEPP systems. A significant body of performance data has accumulated over more than two decades on both U.S. and Russian designs. VNIIEF has devoted much more time and energy to analyzing and modeling the performance of the Russian versions of the switch and their models do a plausible job of predicting system performance from first principles design information.<br><br>VNIIEF models have not been applied to evaluate the performance of U.S. designs and hence the applicability of the VNIIEF models to an extended range of parameters and designs is unknown. VNIIEF has expressed interest in attempting to apply their models to U.S. data, and doing so would be consistent with the programmatic objective of finding topics of truly mutual interest.<br><br>In this project, LANL will provide VNIIEF with performance data, details of the diagnostic measurements used to obtain the data, and designs of the switch assembly – all of which has been published in the open literature over the last 20 years. VNIIEF will endeavor to model the performance of U.S. systems, using VNIIEF models, and will share results of those efforts with LANL. VNIIEF has proposed additional experiments to complete existing data sets, and the value of additional experiments will be evaluated.<br><br>Based on the outcome of the modeling (V&V) effort, extensions of explosive opening switch performance may be possible, and future experimental tests exploring extended performance may be planned |

**Current Status:**

Preliminary technical discussions began at the Megagauss Conference in Novosibirsk in July 2008. Additional technical discussion occurred at the Megagauss Conference in Shanghai, China in July 2010 and the first set of U.S. data was provided to VNIIEF in 2010. VNIIEF has completed, a report summarizing the state-of-the-art in explosive opening switch technology and that report has been received by LANL. Additional technical discussion occurred in Chicago, Sarov and Barcelona in June 2011. Additional results were presented in the Khariton Readings in March 2012 in Sarov and will be documented in the proceedings.

**Publications:**

Ivanov V.A. et a1. Main Types of the Explosive Current Opening Switches and Their Switching Characteristics. XII International Conference on Megagauss Magnetic Field Generation and Related Topics. July 13-18, 2008, Novosibirsk, Russia.

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Duday P.V., Glybin AM., Ivanov V.A. ct aI. Quasi-Trapezoidal Shape ClUTent Pulse Former. Proceedings of *the* 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, November 5-10, 2006, Santa Fe, New Mexico, USA.

**Project Principal Investigators:**

Jim Goforth, (LANL).
Andrey Ivanovsky, Pavel Duday, (VNIIEF).

**Pulsed Power Hydrodynamics**

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| **Project Title:** | ISTC 2403 – (Partner Agreement) Monograph "Magnetocumulative Generators" |
| **Russian Institute:** | Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF) |
| **Brief Project Description:** | Background. During the Cold War, concepts of high-explosive pulsed power (HEPP) generators were developed, initially independently in the 1950s, in the U.S. and Russia largely for their application fusion concepts and later for application to directed energy weapons. The first U.S. insight into Russian work came through an unclassified international conference on High-Magnetic Fields in Frascatti Italy (1965) where researchers from a team including Andrei Sakharov submitted several papers about "magnetic cumulation." The papers were not presented.<br><br>From 1965-1992 the U.S. followed Russian developments in this area through sporadic open literature publications coupled with some technical analysis. In the later years of the Cold War, the possibility of applying this technology to very compact, deliverable, usually electromagnetic, tactical weapons began to emerge alongside interest in large-scale DEW applications for SDI in both countries. HEPP development proceeded more rapidly, and to a higher degree of refinement, in Russia, largely because Russia could not match U.S. and European manufacturing technology for energy storage capacitors. Where the U.S. built large laboratory pulsed power machines, the Russian built small, but expendable, MCG systems of comparable or greater performance. Interestingly, the fact that HEPP/MCG technology does not require a major industrial infrastructure makes this technology accessible to less industrialized nations, rogue nations and extra-national entities. Since 1992, open, cooperative program with Russian laboratories (especially VNIIEF) have largely replaced arm-length speculation about Russian pulsed power technology, and largely validated the most |

interesting reports on large systems accumulated through the period of the Cold War.

Plans for a joint monograph on HEPP were discussed as early as 1983 involving Fowler (LANL) in the U.S., Pavlovskii, Ludyev, and Chernyshev (VNIIEF) in the USSR. Tentative proposals were exchanged, and even a Table of Contents drafted. Ludyev died in 1992 and Pavlovskii died suddenly in February 1993. Fowler retired from LANL (though continued as a limited professional until his death in 2006) and Chernyshev died in early 2005. The first generation technological leaders in this arena have all vanished and their direct protégés are rapidly approaching retirement. Pavlovskii's colleagues again proposed the monograph in the mid-1990s, and the LANL Pulsed Power Hydrodynamic program agreed to support their proposal through the ISTC on the condition that the text would be a truly comprehensive work on the topic (not simply limited to the perspectives of one VNIIEF group). An ISTC Partnership Agreement was executed in FY05.

**Current Status:**

Project Agreement #2403 through the ISTC was approved and funded by ISTC with equivalent LANL partnership support and signed in 2004. In 2008, VNIIEF reported that the effort on the comprehensive manuscript was costing more than initially expected and requested an extension of the duration of the project. Progress was reviewed in July 2010, in August 2011, and again in March 2012 where VNIIEF asserted that the first volume of the book is complete, reviewed and about to be published and that work is continuing on the second volume.

**Project Principal Investigators:**

R.E. Reinovsky, (LANL).
Leonoid Plyashkevich, (VNIIEF editor).

**Pulsed Power Hydrodynamics**

**Project Title:** ISTC# 3164 (ISTC/LANL Partner Agreement) Monograph "Physics Processes in the MAGO MTF System

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Project Description:** The efforts of most laboratories, worldwide, which are engaged in solution of the problem of controlled thermonuclear fusion are directed mainly to studying two physical systems: stationary systems, in which thermal insulation and confinement of a low density, hot, plasma is ensured, using magnetic fields (magnetic confinement systems) and inertial confinement systems in which DT is compressed quite rapidly to high densities (inertial confinement fusion). A third alternate to these two mainline approaches is the research area known as MAGO (abbreviation from MAGnitnoye Obzhatiye—Russian for magnetic implosion) and as MTF (Magnetized Target Fusion) in the United States.

Compared with the direct hydrodynamic compression of initially cold fuel (like in ICF), the MAGO/MTF approach consists of two phases: (1) magnetized, relatively, hot plasma is produced suitable for further compression (with magnetic field ~0.1 MGs having a closed field line configuration; with a plasma iof density ~$10^{18}$ cm-3, temperature ~300 eV, and low impurity content, (because impurities can contribute to the losses due to radiation). (2) the plasma is then compressed quasi-adiabatically by liners (at rates on the order of 1 cm/μs) using powerful magnetic drivers (for example, explosive magnetic generators) in order to heat the plasma to the fusion conditions.

In its time and space scales as well as plasma density scales MAGO/MTF occupies an intermediate position between magnetic confinement and inertial confinement fusion, which differ by about ten orders of magnitude in density and time and by about five orders of magnitude in characteristic sizes. The MAGO/MTF systems are

characterized by high energy densities and strong magnetic fields. Thus, the plasma parameters in MAGO/MTF differ significantly from those in the conventional systems. For numerical simulation, computations of the MAGO/MTF systems must include physical processes, which either have not been studied previously or exhibit new properties. In essence, this approach develops challenging new field of very varied and diverse plasma physics.

The MAGO/MTF development history has lasted for more than twenty years, and a large number of theoretical and experimental papers have been published in that time. These include reviews that discuss the MAGO/MTF concept and integral efforts aimed at demonstration of the overall feasibility of the MAGO/MTF process. There are essentially no reviews devoted to specific physics characteristic of MAGO/MTF despite the fact that researchers have developed theoretical approaches describing the MAGO/MTF plasma radiating properties, the theory of collisionless shock waves essential for these systems, theory of surface discharges important in this research area, and the wall-confinement of the plasma.

Therefore, there is a need for a monograph that would collect and present these effects. The monograph can help young scientists who embark on the studies in the area of MAGO/MTF to gain orientation in the new physical field. The monograph can be useful to interdisciplinary specialists as well, since the results presented can be applied to a wide range of plasma physics effects and hydrodynamics.

**Current Status:**

An ISTC Partnership Agreement has been executed. Progress in the preparation of the manuscript was reviewed in several meetings between LANL and VNIIEF in 2009 and 2010. The manuscript has been completed, translated and delivered to the ISTC and to LANL. Publication, is expected (in English) before the end of calendar year 2012.

**Project Principal Investigators:**

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**Pulsed Power Hydrodynamics**

**Project Title:** ISTC #4047 – (ISTC/LANL Partner Agreement) Monograph "Physics of Imploding Liners"

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Project Descrption:** Since 1992 LANL has been developing the high precision, condensed matter, magnetically driven cylindrical liner as drivers for a variety of materials, EOS and constitutive properties experiments. At the same time condensed matter liners are an integral part of the MTF/MIF approach to alternate fusion concepts. Among the advantages of condensed matter liner are the facts that:

1. Magnetic fields are transparent to x-rays and visible light leading to improved diagnoses of the experiment.
2. Magnetic fields are fundamentally cylindrical (complementing planar gas guns), providing geometries to configurations with convergence plus radial and axial access.
3. Magnetic field drive is "dial-able" and reproducible, demonstrated better than 1% control/reproducibility (limit of measurement).
4. Magnetic fields drive large targets (complementing lasers), affording access to true continuum properties.
5. Magnetically driven liners produce HE shock-like pressure without shocks affording good access to off-Hugoniot states.
6. Electro-magnetic drive delivers energy at "c" without mass (complementing HE) and producing higher material velocities (2X), and reducing collateral damage making confinement or complete containment more practical for a given performance level.

While the work in both Russia and the U.S. (and work conducted jointly) has been documented in both the archival literature and in conference proceedings, there is not a single, comprehensive review of the advances that

have been made in magnetically driven imploding liner technology, including driver technology, high precision fabrication technology, theory describing instabilities and their control, simulation of high performance liners, diagnostics etc. LANL and VNIIEF have agreed upon the feasibility of an ISTC partner project to produce such a comprehensive review in a single, book-length manuscript. Key technical staff in both VNIIEF and LANL, who have been instrumental in propelling the liner physics effort forward for the last two decades are either approaching retirement or have already retired. There is some urgency if these two decades of technical advancement are to be captured.

**Current Status:**

An ISTC manuscript project proposal was prepared by VNIIEF in FY09 and submitted in FY10 with the objective of funding the effort in FY11 and beyond. The formal Partner Agreement has been executed, and incremental funding to the ISTC.

An invitation to the broader scientific community to contribute to the monograph will be issued at the Megagauss Conference in October 2012.

**Project Principal Investigators:**

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Valeriy Yakubov, (VNIIEF).

**Pulsed Power Hydrodynamics**

**Project Title:** ISTC 3237 – (Partner Agreement) Software Package for Studying Properties of Finite Difference Schemes as Applied to Continuum Physics Problems (Master/MAG)

**Russian Institute:** Russian Federal Nuclear Centre-Institute of Experimental Physics (RFNC-VNIIEF)

**Brief Project Description:** Among the collection of computational tools used to conceptualize, design and analyze experimental efforts in advanced hydrodynamics are a suite of 1-D, 2-D and 3-D codes, of which the 3-D multi-physics Advanced Simulation and Computing (ASC) codes are the most sophisticated, capable and in some ways most useful. The disadvantage of the major capability codes is that they require the most capable computing platforms, and a relatively large number of full-time professionals to maintain and adapt the codes, especially to develop the input stream to address new problems. At the other end of the spectrum are the far less capable, but far more accessible, codes that are optimized for use by the non-simulation oriented professional, the experimental scientist and even the student. Under ISTC support, with LANL technical, but not financial, participation, VNIIEF has developed a 1-D hydrodynamic (and MHD) code, designed to be run on a modest desktop or lap-top platform, employing a wide suite of material and constitutive models, a flexible set of drive/boundary conditions and an easy-to-use graphic user interface. This tool would be a significant asset for conceptual development, design and planning of experimental programs involving either high-explosive or pulsed power, or a combination of both drives.

To introduce the code to the (initiallyLANL) experimental community requires:

1. Several licensed copies – or a site-wide license for the code;
2. Expanded documentation, in English, beyond the sketchy documentation that currently exists;
3. Technical support for a period of time to answer questions from new users.

The developers of Master/Mag have proposed a number of useful extensions of the code, which may be useful for

LANL programs including the possibility of a 2-D version of the code as well.

This relatively low cost project will address the three topics needed to introduce the code into regular use and will evaluate the value to be gained by extending the range of code capabilities.

**Current Status:**

LANL participated as a collaborator in the ISTC project that funded the initial development of the code and has exercised the current code in a number of developmental forms. Initial technical discussions with the Rudenko team have been conducted by e-mail and a detailed review of status and plans for the code was conducted during a LANL to VNIIEF visit to Sarov in April 2009. An ISTC Project #3237, for a larger scope of work, which completely included the LANL needs, was authored in 2005, and approved by the ISTC without funding. In a meeting in Moscow in May 2010, VNIIEF and the ISTC agreed that LANL could fund the portion of the #3237 scope of work that was of value to LANL, and that ISTC could convert the project to a Partner Project. The agreement has been completed and funded. Work is in progress.

**Project Principal Investigators:**

R. E. Reinovsky, (LANL).
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