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Penetration Mechanics Research in the Former Soviet Union

Science Applications International Corp., San Diego, CA

Sep 92

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Abstract: Recently published papers by scientists from the former Soviet Union reveal to Western researchers a mature body of highly inventive and dedicated research. To analyze and assess this work, a group of six internationally recognized US experts in the field of penetration mechanics and hypervelocity impact reviewed hundreds of unclassified documents. Five broad, sometimes overlapping, research areas were chosen for assessment: Hypervelocity Impact Capabilities; Penetration Mechanics Experiments at Ordnance Velocities; Analytical Penetration Mechanics; Material Response to High-Velocity Impact and Penetration; and Numerical Simulations of Penetration Physics. Both similarities and differences between Soviet and Western research were noted and characterized, with particular attention paid to potential breakthrough technologies. Leading Soviet scientists and their organizations were identified, as were areas of potentially fruitful collaboration between researchers from the former Soviet Union and the United States. Soviet breakthroughs in penetration mechanics technology that far out-distanced Western efforts were not found, though potential breakthroughs were noted in several areas, including penetration models of brittle materials (principally ceramics), superdeep penetration of particles, and very-high-velocity electromagnetic launchers.

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TECHNICAL ASSESSMENT REPORT

PENETRATION MECHANICS RESEARCH IN THE FORMER SOVIET UNION

W. M. Isbell
C. E. Anderson
J. R. Asay
S. J. Bless
D. E. Grady
J. Sternberg

September 1992

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1710 Goodridge Drive, McLean, VA 22102 (703) 734-5528

FASAC Technical Assessment Report

PENETRATION MECHANICS RESEARCH IN THE FORMER SOVIET UNION

W. M. Isbell
C. E. Anderson
J. R. Asay
S. J. Bless
D. E. Grady
J. Sternberg

September 1992

Science Applications International Corporation
1710 Goodridge Drive, P. O. Box 1303, McLean, VA 22102
10260 Campus Point Drive, San Diego, CA 92121

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ABSTRACT

Recently published papers by scientists from the former Soviet Union reveal to Western researchers a mature body of highly inventive and dedicated research. To analyze and assess this work, a group of six internationally recognized US experts in the field of penetration mechanics and hypervelocity impact reviewed hundreds of unclassified documents. Five broad, sometimes overlapping, research areas were chosen for assessment:

- Hypervelocity Impact Capabilities
- Penetration Mechanics Experiments at Ordnance Velocities
- Analytical Penetration Mechanics
- Material Response to High-Velocity Impact and Penetration
- Numerical Simulations of Penetration Physics.

Two important complementary areas of research, armors and explosives, were not explored.

Both similarities and differences between Soviet and Western research were noted and characterized, with particular attention paid to potential breakthrough technologies. Leading Soviet scientists and their organizations were identified, as were areas of potentially fruitful collaboration between researchers from the former Soviet Union and the United States. Soviet breakthroughs in penetration mechanics technology that far out-distanced Western efforts were not found, though potential breakthroughs were noted in several areas, including penetration models of brittle materials (principally ceramics), superdeep penetration of particles, and very-high-velocity electromagnetic launchers.

The level of former Soviet technologies in the areas assessed is roughly on a par with Western technologies. However, some differences in approaches were striking:

- The Soviet effort appears to have been larger, and more collaborative between organizations, than the US effort.

- Substantial Soviet thrusts in such areas as brittle fracture of ceramics, dynamic viscosity, dilaton theory, and the science of synergetics have had no significant US counterparts.

- Soviet numerical simulation work has emphasized physical understanding (in contrast to greater US emphasis on quantitative modeling using large-scale computations), perhaps reflecting a general shortage of computational capabilities and the unavailability of supercomputers.

The fundamental understanding of material behavior and efficient computer algorithms that have been necessary to perform useful computations on slow computers may yield rapid progress when massively parallel processing computers become more available to penetration mechanics researchers in the Soviet successor states.

Rapid political and economic changes now in progress in the former Soviet Union make confident prognostication impossible. The chapters of this assessment estimate future progress as if it were consistent with that experienced in the period 1980-1990.

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PENETRATION MECHANICS RESEARCH IN THE FORMER SOVIET UNION

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FOREWORD

This report, *Penetration Mechanics Research in the Former Soviet Union*, is one in a series of technical assessment reports produced by the Foreign Applied Sciences Assessment Center (FASAC), operated for the Federal government by Science Applications International Corporation (SAIC). These reports assess selected fields of foreign basic and applied research, evaluate and compare the state of the art in the country or area of interest with US and world standards, and identify important trends that could lead to future applications of military, economic, or political importance. This report, like others produced by the Center, is intended to enhance US knowledge of foreign applied science activities and trends, to help reduce the risk of technology transfer, and to provide a background for US research and development decisions. Appendix E lists the FASAC reports completed and in production.

This report was prepared by a panel of internationally recognized scientists who are active in penetration mechanics research:

• William M. Isbell (Panel Chairman)	Principal Scientist Kinetic Energy Weapons Group General Research Corporation
• Dr. Charles E. Anderson	Manager, Ballistic Sciences Section Materials and Mechanics Department Southwest Research Institute
• Dr. James R. Asay	Manager, Computational Mechanics and Adaptive Structures Department Sandia National Laboratories
• Dr. Stephan J. Bless	Technical Director for Impact and Penetration Physics Institute for Advanced Technology
• Dr. Dennis E. Grady	Distinguished Member of Technical Staff Experimental Impact Physics Department Sandia National Laboratories
• Dr. Joseph Sternberg	Professor US Naval Postgraduate School

On a part-time basis over the period from June 1991 to March 1992, each panel member devoted a substantial amount of time assessing published Soviet literature on penetration mechanics research, much of it from the large private library of Dr. Joseph E. Backofen, Jr., a long-time student of such work. Efforts were made by the panel and by SAIC to identify and acquire as many relevant Soviet publications as possible, subject to constraints of availability and search criteria. This assessment is based on a review of available Soviet literature published up through 1991, as well as personal interaction with scientists in the former Soviet Union (including some discussions after the dissolution of the Soviet Union). The assessment is thus primarily of research accomplishments and capabilities prior to the break up of the Soviet Union. The panel is aware of subsequent disruptions, but could not analyze their effects because it is too soon to examine post-dissolution research. Because of the cut-off date for the research reviewed, this report uses the term "Soviet" to describe the nationality of the research and researchers. Principal Soviet technical publications reviewed by the panelists are listed in Appendix C.

EXECUTIVE SUMMARY

BACKGROUND

Modern technology in penetration mechanics and hypervelocity impact began with the development of adequate instrumentation in the 1930s and 1940s. Instruments such as flash x-ray, high-speed streaking and framing cameras, and new short-duration light sources, allowed researchers for the first time to visualize dynamic processes that are unobservable to the human eye. These observations allowed development of the first useful predictive models of material behavior, and of insight into the fundamentals of penetration. These technologies thrived during World War II to support development of the Bazooka hypervelocity anti-tank weapon and nuclear weapons (initiated by shockwave compression of materials).

During this period, Soviet and Western approaches began to diverge. The Manhattan Project spurred the development of early high-speed electronic computers, which subsequently provided the West with an enormous lead in computational capability. This capability supported a degree of design sophistication in the United States that led to miniaturization of items ranging from nuclear weapons to rocket boosters, and a reliance on sophisticated technologies rather than more brute-force approaches. This distinctive style, which has no counterpart in the former Soviet Union, characterizes US development efforts to this day.

Western investigators' ability to perform large-scale calculations of material and structural behavior under shockwave loading has now become the mainstay of many US efforts to develop new weapon concepts and to optimize weapon effectiveness. This, too, has no visible equivalent counterpart in Soviet development work.

COMPUTATIONAL CAPABILITIES

Lack of computational capability is everywhere evident in early-1980s Soviet investigations into shockwave propagation and fracture. This slowed Soviet research in some areas, especially in multi-dimensional problems requiring many points in the computational grid.

Soviet computational penetration mechanics researchers were strongly influenced by published US finite element calculations. While the former Soviet Union has followed the US lead in this area in general, Soviet scientists have emphasized certain areas of penetration and fracture more strongly than their colleagues in the United States. In particular, in the important area of material damage, Soviet models are different; some are considerably more advanced.

Rapid advancements are now possible in computational capabilities as more sophisticated computers (particularly massively parallel processor computer systems) become available in the successor states of the former Soviet Union. User-friendly computational capabilities, which stress the use of hydrocodes by experimenters and engineers rather than only by computer experts, are being developed.

EXPERIMENTAL CAPABILITIES

It is frequently difficult to determine precisely which test techniques have been used and precisely what results have been obtained from Soviet publications. Details are omitted, experimental techniques may not be described, and error bars may not be included. However, enough information is included to indicate that many Soviet experimental techniques have followed a different course than those in the United States.

In the United States, early shockwave research used explosives to generate pressures in the range 10 to 50 GPa (100 to 500 kbars). During the 1960s, single- and two-stage light gas guns were developed that extended the pressure range an order of magnitude higher and lower, to 1 to 600 GPa. These guns provided researchers with excellent control over both pressure and waveshape. Advanced instrumentation, such as laser interferometry, flash x-ray systems, and in-material stress gages, provided measurements precise enough to validate new models of material behavior.

Since the late 1950s, Soviet researchers have continued to develop explosive techniques that allowed them to far surpass US capabilities in some areas. Soviet explosively driven systems have routinely accelerated flyer plates to >15 km/s, and produced pressures in the range of 1,000 GPa. This capability has been available to Soviet researchers since the 1960s, and today can attain higher pressures than US gun techniques. While an increasing number of tests performed on guns have been reported, explosive techniques still play a major role in Soviet investigations.

As in the United States, experimenters in the former Soviet Union have been developing electromagnetic (EM) launchers (railguns) of various types, with a goal of attaining higher velocities than available with gas guns. Velocities to 7.4 km/s have been achieved with gram-sized projectiles, comparable to US and Japanese efforts. Because high velocities with EM guns are typically associated with plasma-drive armatures, the collaboration between extremely capable plasma scientists and the launcher development groups in the Soviet successor states could lead to breakthroughs in velocity capability.

Soviet instrumentation and diagnostics have reached a par with Western techniques, in the sense that a full complement of instruments has been used to measure shockwave and penetration parameters. Soviet researchers have used manganin piezoresistive stress gages to measure *in-situ* shockwave profiles and variable capacitance transducers for measurement of the free surface motion of shocked specimens (a technique now largely abandoned by Western researchers in favor of laser interferometric methods). US researchers routinely employ a wider range of instrumentation, including laser interferometry, piezoelectric gages, electromagnetic gages, and a wide variety of other profile-measurement devices. However, advanced techniques such as interferometry have been used in recent Soviet studies.

Soviet researchers have used the experimental capabilities described above to compile an extensive library of equations of state, over a broad range of pressures. Some components of this library are better than those available to Western researchers, especially in the areas of expanded state equations of state and shockwaves in porous materials. Many penetration and hypervelocity impact studies are dependent on the quality of the equations of state, constitutive models, and associated spallation and fracture strengths used in their design and interpretation. This makes the Soviet library a valuable asset.

ANALYTICAL AND THEORETICAL CAPABILITIES

The massive efforts mounted by Soviet scientists to understand the basic phenomena of penetration have resulted in some surprising and useful theories, often based on innovative analytical methods. Entirely new formulations, such as the science of synergetics of deformable media (which relates high-rate flow to the turbulent fractal nature of dissipative structures), have been investigated. Some important topics of Western research (for instance, material failure by adiabatic shear banding) have been relatively ignored.

Some of the new Soviet theories attempt to explain a phenomenon referred to as "superdeep penetration," in which hard microparticles, launched at modest velocities of a few kilometers per second, penetrate an order of magnitude or deeper into a target than predicted by conventional cratering theories. This phenomenon has attracted the interest of several of the most capable and prestigious shockwave scientists in the former Soviet Union, and has become a focal point in comparing new theories.

Soviet advances in modeling the penetration of ceramics, where a concept of "failure waves" leads to two modes of penetration (depending on whether the projectile exceeds or lags the failure wave velocity) are of substantial interest. US efforts in ceramic armor research may benefit from examination of these theories and the data reported to support them.

PROMINENT SOVIET INSTITUTES AND RESEARCHERS

The Soviet effort in hypervelocity impact and penetration mechanics has employed several times the number of researchers as does the United States effort. Collaboration between these researchers and between their institutes has been considerable, further increasing the effectiveness of the Soviet system. Long-term Soviet government support of these disciplines has allowed strong, stable programs to be organized. Their longer-term funding has allowed Soviet researchers to develop programs that are more logical and consistent than their US counterparts.

Tables at the end of each chapter in this assessment list Soviet institutes participating in the aspect of penetration mechanics research discussed in that chapter, along with the names of important researchers and a list of references and recommended readings. Chapter I ends with a consolidated list of key penetration mechanics research facilities.

Many nationally and internationally prominent scientists have participated in hypervelocity and penetration mechanics research in the former Soviet Union, including several Academicians and heads of laboratories. Among the outstanding Russian scientists who cross several disciplines pertinent to penetration mechanics are Vladimir Ye. Fortov, who holds a joint appointment as Director of Physical Dynamics at the Chemical Physics Institute (Chernogolovka) and at the High Temperatures Institute (Moscow/Chernogolovka), and A. S. Balankin, a highly innovative theoretician at the Moscow Engineering Physics Institute.

Collaboration between institutes has been a strong asset of Soviet penetration mechanics research. In other areas of Soviet science, it has been noted that a strong institute leader dominated the thinking of the group to an extent that made meaningful technical exchanges with other research groups difficult. No such phenomenon was noticed in the disciplines examined in this assessment.

POTENTIAL TECHNOLOGICAL BREAKTHROUGHS

Soviet breakthroughs in penetration mechanics technology that far outdistanced Western efforts were not found, though potential breakthroughs were noted in several areas, including penetration models of brittle materials (principally ceramics), superdeep penetration of particles, and very-high-velocity electromagnetic launchers.

AREAS OF POSSIBLE COLLABORATION

This panel identified areas where collaboration between the United States and the successor states of the former Soviet Union could advance US capabilities, particularly:

- Promising areas that have few or no US counterparts; a result of dissimilarities in the development of penetration mechanics research in the former Soviet Union and the United States.

- Areas that are not necessarily unique, but that could readily add to US capabilities.

- Areas where Soviet databases or physical models are superior or complementary to their US counterparts.

Table 1 lists the candidate areas and their priorities.

Table 1
TECHNOLOGIES FROM THE FORMER SOVIET UNION THAT COULD BENEFIT US PENETRATION MECHANICS RESEARCH

Area		Institute	Researcher	Application
Explosive drivers	1,2	Chemical Physics Institute	Fortov	High-pressure EOS, debris shields
Transfer of material models	1	High Temperatures Institute	Kanel'	
Transfer of synergetics concepts	1	Moscow Engineering Physics Institute	Balankin	New approaches in shock waves, penetration, fracture
Summary of EM technology	3	Lavrent'yev Hydrodynamics Institute	Lebedev, Shevtsov	Summary of techniques, models
Expanded state EOS	3	Chemical Physics Institute	Fortov	Better hypervelocity impact modeling
Superdeep penetration	1	Applied Physics Problems Institute, Mechanics Scientific Research Institute	Romanov, Chernyy, Grigor'yan	Advanced target damage mechanism
High-pressure EOS computer data base	1,3	High Temperatures Institute	Fortov	Modeling and simulation
Numerical damage models for hydrocodes	2	Applied Mathematics & Mechanics Institute	Belov, Gorel'skiy, Khorev	Modeling and simulation
Electromagnetic armor	1,2	Mechanics Scientific Research Institute	Bagdoyev	Potential advanced armor
Porous materials models	3	Ioffe Physical Technical Institute	Kozhushko	Energy dissipation, advanced armors
Various experimental diagnostics	1,3	Various	Various	Experimental work
Compilation of spallation data and wave profiles	3	Experimental Physics Institute, Chemical Physics Institute	Novikov, Kanel'	Expanded data base
EM gun barrel and manufacturing technology review and assessment	1,2	Lavrent'yev Hydrodynamics Institute	Shvetsov	Inexpensive barrels
Summary of shield design, on-board diagnostics, and results of Vega mission	1	High Temperatures Institute	Fortov	Future US space experiments
Statistical fracture models	2	Continuum Mechanics Institute	Naymark	Impact damage modeling
Computational plasticity models, advanced deformation theory	2	Lavrent'yev Hydrodynamics Institute	Merzhiyevskiy	Hypervelocity and conventional impact models
High-speed penetration of ceramics	2	Ioffe Physical Technical Institute	Kozhushko	Ceramic armor

Key:
1. Unique, no US counterpart
2. Not unique, but may be readily available from the former Soviet Union
3. Substantial database in the former Soviet Union

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CHAPTER I
ASSESSMENTS

A. INTRODUCTION

Soviet[1] research in hypervelocity impact and penetration mechanics has progressed along a broad and vigorous front for decades, producing knowledge and capabilities very much on a par with Western technology. Different development paths have been followed in the former Soviet Union and in the West, producing advantages for each side in different areas.

Soviet research has employed more workers and has produced larger and (in some respects) more complete databases. Institutes and researchers in the former Soviet Union have tended to collaborate with one another more than their Western counterparts. Soviet programs were planned and executed over longer periods of time.

While Soviet weapons research was not examined in this assessment, all of the penetration and hypervelocity impact mechanics components needed to support nuclear and conventional weapons development are obviously in place.

The apparent pace of development of innovative Soviet models of physical phenomena related to penetration mechanics and hypervelocity impact accelerated in the mid- and late-1980s. This is evident in the difference in conclusions between this assessment and a related 1988 FASAC assessment of Soviet dynamic fracture mechanics research, where it was noted that "the Soviet approach seems more traditional than in the West and there is less evidence of reexamination with new innovative approaches."[2]

Publications describing new Soviet experimental data and new Soviet models of material behavior now abound. Whether publication of this information signifies a

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[1] This report will use the term "Soviet" to describe the nationality of the research and researchers, reflecting the situation when most of the assessed research was performed.

[2] W. G. Knauss, J. P. Dempsey, L. B. Freund, H. T. Hahn, A. S. Kobayashi, J. F. Mescall, and W. A. Nash, *Soviet Dynamic Fracture Mechanics Research*, Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, Feb 1988, I-1.

general change in philosophy toward increased "openness" or is due to the rise and inclinations of particular individuals remains to be seen.

B. HYPERVELOCITY IMPACT RESEARCH

Physical models of hypervelocity impact, hypervelocity launchers, and high-speed diagnostic instrumentation are needed to understand material behavior at extremes of pressure and temperature. This understanding can in turn support development of advanced nuclear and conventional weapons, enhanced understanding of astro- and planetary physics, and practical applications (such as debris shields for spacecraft).

Beginning in the late 1940s, Soviet researchers developed explosive techniques to launch flyer plates into material specimens, eventually attaining velocities up to 15 km/s. These techniques have been refined and used to produce an extensive database of high-pressure equations of state, including an excellent compilation on expanded states and compression of porous materials. These Soviet techniques can produce higher pressures in large specimens than do the light gas gun techniques more commonly used in the West. Only underground nuclear tests produce higher experimental pressures over significant volumes. (Microparticles accelerated by electrostatic acceleration to velocities >100 km/s produce yet higher pressures, but only in extremely small volumes.)

Despite their success with explosive launchers, Soviet use of hypervelocity guns has apparently increased. Vigorous development of Soviet electromagnetic (EM) launchers is also evident, with some recent examples matching the United States in velocity (>7 km/s). Such guns find use in the laboratory and in ballistic studies, and could provide a basis for advanced kinetic energy weapons. As in the United States, efforts in the former Soviet Union are spread over a variety of electromagnetic launchers, including rail guns and coil guns. No evidence was found of Soviet development of large-scale (>100-mm bore diameter) guns, though such work may be going on in classified programs.

Long-established Soviet capability in explosive forming has been used to form rapidly and inexpensively the complex barrels necessary for rail guns. This technique may speed Soviet development of these guns, since parametric studies of barrel configurations are more practical when many barrels can be made quickly and cheaply.

Close collaboration between Soviet plasma physicists and the EM gun designers may support breakthroughs in very high velocities, because in order to increase the velocities beyond those currently achieved it will be necessary to understand more completely the details of the plasma armature used to drive projectiles in high-velocity (>3 km/s) EM guns. Researchers from several plasma research communities, including controlled fusion and laser deposition, have been participants in Soviet EM gun efforts.

Design of the debris shield for the Vega space probe's mission to transit the tail of Halley's Comet is an excellent example of Soviet capabilities and cooperation in hypervelocity science. An inter-laboratory Soviet team, headed by V. Ye. Fortov, produced a lightweight shield to protect the spacecraft from impacts of small particles at velocities greater than 80 km/s. The team included shock hydrodynamicists, computer modelers, instrumentation specialists, structural engineers, and operators of ground-test facilities capable of launching small particles to >30 km/s. Successful completion of the mission resulted in award of the Order of Lenin to Academician Fortov.

C. PENETRATION MECHANICS AT ORDNANCE VELOCITIES

Soviet investigations of penetration at ordnance velocities have followed the same general lines as Western experiments and analyses. In some areas, including modeling of the penetration of ceramics, the superdeep penetration phenomenon, and new theories of the stability of shaped charges, Soviet work appears to be oriented differently than Western efforts. In other areas, such as penetration into ductile metals, recent published Soviet work has been less distinguished than Western research (though earlier Soviet work was more advanced than its Western counterpart).

Soviet research on penetration into heavy ceramic armor reflects more advanced thinking than Western work, formulated in a different conceptual framework. Their development of concepts of a characteristic "failure wave," related (probably) to tensile failure in the ceramic, and preceding the projectile cavity, has important implications for ceramic armor failure, especially at very high impact velocities, because it implies a marked decrease in penetration when the penetration velocity exceeds the failure wave velocity. These formulations may provide a key to understanding the time dependence of ceramic armor penetration at very high strain rates. Soviet experimental results support this hypothesis, leading to substantially higher apparent strength for ceramics (and correspondingly lower effectiveness of projectiles) at higher velocity. This theory implies that resistance to penetration in ceramics can be achieved by lowering the speed of the failure wave. The considerable body of Soviet high-velocity work on penetration of porous silicon carbide may be an effort to test and exploit this hypothesis. Other Soviet studies claim to have achieved ceramic strengths 50 percent of theoretical, a capability that would be of great interest to US designers of ceramic armor.

Spallation of metals and methods of suppressing spall have received considerable attention in Soviet research, as they do in the West. Understanding of spallation processes appears equivalent, although Soviet theories on damage accumulation and crack propagation are novel enough to be of interest to Western scientists, as are the advanced algorithms used in Soviet computer routines. The substantial spallation database compiled by penetration mechanics scientists in the former Soviet Union is a valuable asset in validating material models and in comparing the properties of different armor and shield materials. Access to this database could assist Western researchers in several areas.

Soviet studies of the properties of electromagnetic armors have been substantially more complete than corresponding Western studies. If electromagnetic armor is feasible (an assumption as yet unproved), the former Soviet Union appears to be closer to achieving a working armor than is the West.

Stretching and subsequent segmenting of the shaped-charge jet is thought to hamper armor penetration by shaped charges. A. S. Balankin and colleagues have put forward novel and interesting theories of jet formation, in which jet breakup is due to initial microcracks in the shaped charge rather than instabilities in the jet (as influenced by its initial conditions).

D. MATERIAL RESPONSE TO HIGH-VELOCITY IMPACT AND PENETRATION

Soviet modeling and experiments to examine high-velocity impact, penetration, and material failure have employed innovative analytical methods. Experiments most often used explosive loading techniques, though guns have played an increasingly important role recently. Other dynamic loading techniques, such as Split-Hopkinson bars and Taylor impact methods, are less utilized than in Western studies.

Soviet impact and penetration researchers have developed interesting new techniques and innovative ways of using standard experimental methods. Unfortunately, the techniques are rarely well explained or illustrated in Soviet publications. Soviet time-resolved diagnostics have included variable capacitor transducers (a technique now regarded as outmoded in the West), manganin stress gages of arbitrary orientation, quartz gages, optical lever arms, and other techniques well known to Western scientists. The VISAR interferometer, which is becoming the standard technique in the United States for highly resolved measurements of surface motion, has been utilized in the former Soviet Union in several clever applications. A unique Soviet experimental technique using radioactive tracers to measure material flow has led to the discovery of anomalous mass transport by shockwave processes and during long-rod penetration.

There has been concerted and systematic Soviet effort to bring computational capabilities to maturity, with realistic models of material behavior. Advanced constitutive models, including numerical models of ultra-high equations of state, viscoelasticity, transformation kinetics, and porous material models, were used in recent Soviet research.

Basic Soviet studies of dislocation dynamics employ very contemporary theories of dislocation evolution in shock and dynamic deformation. Soviet researchers have developed dilaton theory as a physical basis for the kinetic theory of spall and extended that theory to address nucleation and growth of dislocation structures in the shock front. Dilaton theory has provided a unifying basis in fluctuation physics for earlier kinetic theories that treated specific atomic and thermodynamic properties, and has become widely accepted by Soviet workers in the field. Originally developed to describe spall, it is being extended (by other Soviet workers) to dynamic plasticity, shock deformation, and explosive initiation.

An extensive Soviet effort on creep, fatigue, and spall has resulted in a fully coupled dynamic and static model, computationally implemented in their hydrocodes. Coupled continuum damage models and failure criteria contained within a strong thermodynamic framework enhance the capabilities of their numerical simulations.

An intriguing new science, termed synergetics, has been emerging in the Soviet literature and may provide breakthrough understanding of the high-rate deformation processes in terms of energy and entropy production principles. Soviet researchers have actively applied these principles to a wide variety of dynamic loading problems, including fracture, phase transformation, and penetration into porous and brittle solids. Further development of the synergetic models may stimulate the next generation of Soviet research in the field.

E. NUMERICAL SIMULATIONS OF PENETRATION PHYSICS

It is in the area of numerical simulations that the largest gap has existed between US and Soviet penetration research. Lack of supercomputer power has affected the entire approach of Soviet impact physics. Now that massively parallel processing computers are becoming available to scientists in the successor states of the former Soviet Union, this gap has been rapidly narrowing.

Early Soviet work primarily utilized Eulerian hydrocode formulations for calculations of large-deformation material response. Later work has included both Lagrangian and Eulerian-Lagrangian combinations. The most recent numerical models include many of the features found in US hydrocodes. Early Soviet work on calculating shockwave profiles involved introducing viscous effects into the constitutive behavior of metals. When a US researcher published a methodology for separating the elastic and plastic portions of the wave, giving rise to elastic precursors, Soviet researchers soon adopted his approach into their computer formulations.

Published Soviet penetration and impact calculations now include two- and three-dimensional impacts of rods, spheres, and plates into a wide variety of materials and shapes. The constitutive relations used, including time-dependent material failure models, are more advanced than their US counterparts (though the Soviet work has been influenced by published US research).

Some Soviet hydrocodes have been made directly available to penetration and impact scientists and engineers who are not specialists in their use. These researchers have been able to set up rather complicated problems (for example, hypervelocity impact on a two-layer spacecraft shield involving three-phase equations of state) and obtain answers in relatively short times. In some ways, this capability is in advance of routine US practice. In the main, however, great disparity between Soviet and US capabilities in computational power has been evident in the types of problems Soviet researchers have attempted and the reliance of Soviet scientists on massive amounts of experimental data to support their extrapolations and predictions.

Researchers in the former Soviet Union frequently model early-time response using the Eulerian particle-in-cell (PIC) method, followed (as the deformations become large enough to be computationally unmanageable) by mapping into a Lagrangian grid to continue the calculation. The PIC methodology should run well on computers with massively parallel processing (MPP); each processor could calculate the movement of a small number of particles. Rapid advances in calculational capability may therefore occur as MPP machines become more readily available in the Soviet successor states.

F. KEY RESEARCH FACILITIES

Table I.1 is a consolidated list of key research facilities. Figure I.1, following the table, indicates the locations of the institutes listed. While many organizations are grouped in the Moscow area, others are located quite remotely. Travel between these widely dispersed research sites has quite likely been an impediment to research progress, a problem that may grow in the future.

Table I.1

KEY PENETRATION MECHANICS RESEARCH FACILITIES IN THE FORMER SOVIET UNION

Institute	Location
Applied Mathematics & Mechanics Institute, Tomsk State University im. V. V. Kuybyshev	Tomsk (Russia)
Applied Physics Institute	Novosibirsk (Russia)
Atomic Energy Institute im. I. V. Kurchatov	Moscow, Troitsk (Russia)
Belorussian State University im. V. I. Lenin	Minsk (Belarus)
Chelyabinsk facilities (unnamed)	Chelyabinsk (Russia)
Chemical Physics Institute, Russian Academy of Sciences	Chernogolovka (Russia)
Computational Center, Siberian Branch, Russian Academy of Sciences	Novosibirsk (Russia)
Continuum Mechanics Institute, Russian Academy of Sciences	Perm' (Russia)
High Temperatures Institute, Russian Academy of Sciences	Moscow, Chernogolovka (Russia)
Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, Russian Academy of Sciences	Novosibirsk (Russia)
Istra (facility unnamed)	Istra (Russia)
Machine Science State Scientific Research Institute im. A. A. Blagonravov, Russian Academy of Sciences	Gor'kiy/Nizhniy Novgorod[3] (Russia)
Materials Science Institute, Ukrainian Academy of Sciences	Kiev (Ukraine)
Mathematics Institute, Siberian Branch, Russian Academy of Sciences	Novosibirsk (Russia)
Mechanics Scientific Research Institute, Moscow State University im. M. V. Lomonosov	Moscow (Russia)
Mining Institute	Novosibirsk (Russia)
Moscow Science Center (several facilities)	Chernogolovka (Russia)
Moscow State University im. M. V. Lomonosov	Moscow (Russia)
Optical Physical Measurements All-Union Scientific Research Institute, Russian Academy of Sciences	Moscow (Russia)

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[3] In late 1991, Gor'kiy resumed its historical name, Nizhniy Novgorod.

Table I.1
KEY PENETRATION MECHANICS RESEARCH FACILITIES IN THE FORMER SOVIET UNION (cont'd.)

Institute	Location
Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences	Leningrad/St. Petersburg[4] (Russia)
Powder Metallurgy Scientific Production Association	Minsk (Belarus)
Siberian Branch, Russian Academy of Sciences	Novosibirsk (Russia)
Space Research Institute, Russian Academy of Sciences	Moscow (Russia)
Strength Problems Institute, Ukrainian Academy of Sciences	Kiev (Ukraine)
Theoretical Physics Institute im. L. D. Landau, Russian Academy of Sciences	Chernogolovka (Russia)
Tomsk State University im. V. V. Kuybyshev	Tomsk (Russia)

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[4] In late 1991, Leningrad resumed its historical name, St. Petersburg.

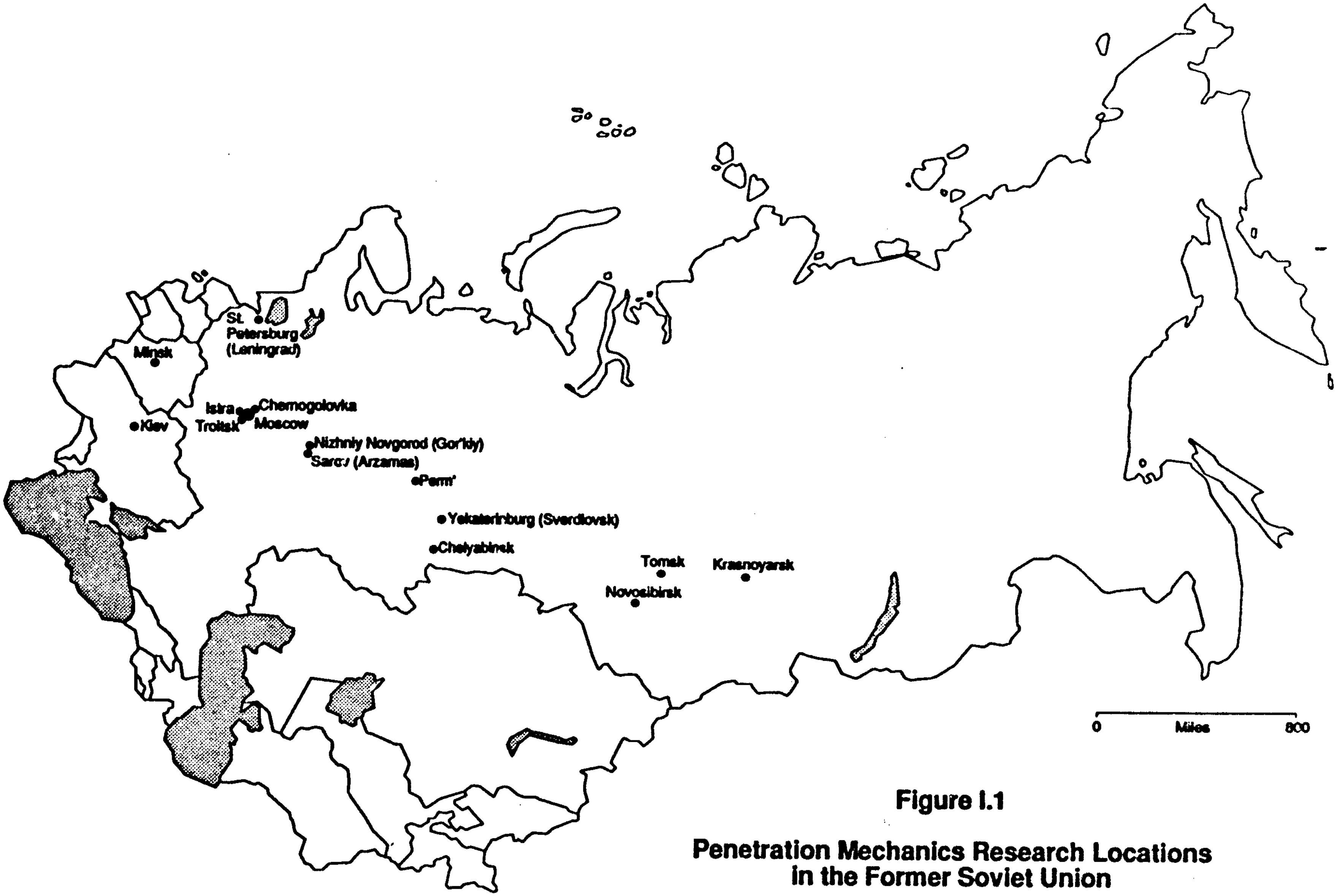

Figure I.1

Penetration Mechanics Research Locations
in the Former Soviet Union

CHAPTER II

PENETRATION MECHANICS EXPERIMENTS AT ORDNANCE VELOCITIES

A. SUMMARY

This chapter examines Soviet research in terminal ballistics, with an emphasis on experimental projects. Its scope also includes concepts and methodologies for armor and penetrator design.

Soviet literature has been more circumspect than Western literature in omitting any mention of specific armor designs. However, there is a great deal of discussion of the basic technology of penetration mechanics and impact behavior of materials.

In many aspects of penetration mechanics, Soviet researchers seem to have based their work on principles that are relatively unknown in the West. The most important such area is probably ceramic armor, where Soviet publication of analytical and phenomenological work has led the West by several years. Other areas of Soviet leadership have included concepts for breakup of shaped-charge jets, electroplastic phenomena, and spall suppression with porous materials. This lead in basic research should raise concern about technological advantages in ceramic armor and electromagnetic armor design.

There is little evidence that the Soviet Union developed important technologies concerning penetration of armors or penetrator development that have not been explored by Western researchers. However, the phenomenon of superdeep penetration of metals deserves careful scrutiny. Soviet reports have only described this process for very small particles, but if the mechanism could be manipulated to work on a macro scale, it would be extremely significant.

Soviet researchers have also published extensively concerning the dynamic properties of materials that are used in terminal ballistic technology. These data can be a useful resource for Western analysts.

B. INTRODUCTION

Advances in armor and projectile technology depend on evolution of new materials and new configurations. For example, in the West, many armor improvements have resulted from the introduction of fiber-reinforced composites based on new fibers (such as aramid and polyethylene) and use of ceramics. Meanwhile, new research on configurations has focused on use of explosives (for example, reactive armor) and heavily confined ceramics.

C. DISCUSSION

1. Ceramic Armor

Ceramic armor was initially developed in the West in the 1960s. The application was primarily small caliber threats, such as .30- and .50-caliber bullets. Although predictive capabilities were not established, the principles of ceramic armor design were elucidated in a series of reports from Lawrence Livermore National Laboratory that have become standard reference documents.[1] Additional research was conducted in the 1970s as new materials became available. During the period covered by this assessment (1980s), the Soviet literature contained little concerning lightweight ceramic armor, even though this has remained a common research topic in the West.

Starting in the mid 1980s, a major thrust in the United States has been to use ceramics for heavy armor. That work has met with mixed success, both from practical and theoretical points of view. Most of the major conceptual developments in ceramic armor that have been developed in the United States in the past five years can be found in considerably earlier Soviet publications. In addition, there are models for ceramic failure under impact that have yet to appear in the Western literature (either open or closed). One must assume that Soviet researchers have been several years ahead of those in the West in research on ceramic armor. As in other

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[1] M. L. Wilkins, R. L. Landingham, and C. A. Honodel, "Fifth Progress Report Light Armor Program," UCRL-50980, 1971.

M. L. Wilkins, "Third Progress Report of Light Armor Program," Lawrence Radiation Laboratory, Livermore, California, UCRL-50460, July 1968.

areas of penetration mechanics, no Soviet publications describe armors that may be prototypes for fielded systems. Very few papers even deal with impact scenarios that represent expected battlefield threats (for example, Zil'berbrand et al., 1989). However, if practical heavy ceramic armors can be developed, the successor states of the former Soviet Union may well have a significant lead.

a. Impact and Penetration Mechanics of Ceramics

Several concepts that are unfamiliar to most Western workers have permeated most Soviet writing on effects of impact on ceramics. Some of these, such as dilatons, are discussed in Chapter IV, but perhaps chief among these is the idea that ceramics fail at a characteristic velocity. This is often called the failure wave velocity, and is usually denoted C_F in Soviet literature. This concept was noted in an earlier FASAC assessment on fracture mechanics,[2] but the references cited in the FASAC assessment were rather old, and did not mention the fact that failure waves are discussed in even the most recent Soviet articles on ceramic armor.[3] The basic concept of failure waves is that since failure can only take place at the speed C_F, very different penetration phenomena are observed depending on whether or not the penetration velocity, u, is greater than or less than C_F. In particular, ceramics are *much* stronger when $u > C_F$.

There are few, if any, cases of interest to Western scientists for which $u > C_F$. Thus, one wonders why Soviet researchers placed so much attention on this penetration region. As discussed below, reasons may include development of special ceramics with lower C_F values, models for effects of boundaries on penetration resistance of ceramic tiles, or use of ceramics against shaped-charge jets and other hypervelocity projectiles. US workers have spent a great deal of time trying to determine the behavior of ceramics that have failed (for the case $u < C_F$), but most models to date are only descriptive (for example, they do not explain why strength levels are mani-

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[2] W. G. Knauss, J. P. Dempsey, L. B. Freund, H. T. Hahn, A. S. Kobayashi, J. F. Mescall, and W. A. Nash, *Soviet Dynamic Fracture Mechanics Research*, Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, Feb 1988.

[3] Failure wave concepts can be found in the following references: Nikolayevskiy, 1979, 1980; Balankin et al., 1989a; Cherepanov, 1979; Finkel', 1970; Slepyan, 1968; Galin et al., 1967; among others.

fested). According to Galanov et al. (1989), Soviet researchers also had not made much progress on this problem.

The failure wave concept is also applied to glassy polymers (for example, Yeremenko et al., 1989), and sometimes to metals (for example, Balankin, 1988a). It appears to have been developed as a result of extensive studies of penetration of brittle plastics over 20 years ago. (Use of plastics as surrogates for ceramics has only recently been tried by Western researchers.)

Along with the concept of characteristic failure velocity, Soviet researchers have written about delayed damage under impact loading (for example, Zlatin et al., 1985). Delayed damage is an important concept for ceramic armor because it gives rise to dwell times—meaning that penetration does not commence on impact, but some time later. Of course, penetration dwells are very destructive to projectiles. Dwell times are explained by failure wave transit times, both for heavy and for light weight armor (Zil'berbrand et al., 1989). US researchers, by contrast, have not generally focused on the importance of dwell times in ceramics.

This conceptual framework has led Soviet researchers to suppose that ceramics will exhibit enhanced strength when subjected to hypervelocity impact. This concept seems almost totally absent from Western literature. For metals, high-velocity penetration resistance is mainly inertial, but for ceramics, in the Soviet view, it also arises from a need to disassociate the ceramic because it does not have time to undergo normal brittle failure (which involves microcrack propagation).

Brittle failure under impact is associated with active dilation of ceramics according to most Soviet writers (see Zlatin et al., 1986, for example). Western authors have also recognized the importance of this effect, but this panel is unaware of any quantitative treatments. Some researchers at the Ioffe Physical Technical Institute in Leningrad[4] have contrasted dynamic failure with static failure:[5] in static failure the failure takes the path of least resistance and is dominated by defects, whereas in

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[4] Leningrad recently resumed its historical name, St. Petersburg. As most of the research reviewed for this assessment predated this change, Leningrad will be the primary designation used here.

[5] For example, Izotov and Lazarev, 1986; Lazarev et al., 1986.

dynamic loading the process is "quasi-microscopic, dissociative," and atomic bonds are broken in one vibration period.

As in the West, penetration of ceramics is normally discussed in terms of modified Alekseyevskiy-Tate theory.[6] However, whereas in the West this has only become accepted in the past couple of years,[7] researchers in the former Soviet Union have been openly publishing these concepts for over a decade. In 1984, for example, Tate modeling of ceramics was presented at a Western conference (Lazarev et al., 1986).

The essentials of Alekseyevskiy-Tate theory are the following: penetration is mainly steady-state (for example, there is a constant penetration velocity, u), and the target penetration resistance can be summarized in a single parameter, R_t, which in the West is usually called "target resistance." In the Soviet literature, "hardness" is used instead of R_t, and is usually denoted H. Soviet values of H are given in Table II.1. These values began appearing in the Soviet literature in 1987 in publications by the Ioffe Physical Technical Institute.

These values of R_t for ceramics are typically four times higher than values reported in Western literature (much of which is classified)! The values for metals are similar to Western values.

However, researchers in the former Soviet Union do not measure R_t the same way that Western scientists do. Western scientists shoot ordnance velocity tungsten rods (for example, at about 1.5 km/s) through large well-confined ceramic tiles and derive the penetration velocity one way or another,[8] often indirectly. Soviet researchers have shot at thin tiles (typically 15-mm thick) and measured impact and exit times of copper rods striking at 5 km/s or higher. Thus, the measurements are

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[6] A. Tate, "Further Results in the Theory of Long Rod Penetration," *J. Mech. Phys. Solids*, 17:141 (1969).

[7] For example, Z. Rosenberg and J. Tsaliah, "Applying Tate's Model For the Interaction of Long Rod Projectiles with Ceramic Targets," *Int'l. J. Impact Engr.*, August 1989; and G. Hauver, "Ballistic Evaluation of Ceramics (U)," *Proc. Combat Vehicle Survivability Symp., 1, 26-29 Mar 1990,* 1991. A recent US army report is qualitatively and quantitatively similar to this Soviet work: G. E. Hauver, P. H. Netherwood, R. F. Benck, A. Melani, *Penetration of Shaped-Charge Jets into Glass and Crystalline Quartz*, BRL-TR-3271, Sept 1991.

[8] Rosenberg and Tsaliah, 1989; G. Hauver, 1991.

not directly comparable, since the dynamic pressures in the Soviet tests have been about an order of magnitude higher than in Western experiments. Western scientists have not determined R_t from high-speed copper projectiles, and Soviet scientists have not published R_t measurements derived from conventional penetrator impacts. It is very unlikely that Soviet researchers have not made these measurements. Most likely, the results have been considered too sensitive to publish.

Table II.1
PENETRATION RESISTANCE OF CERAMICS

Material	Hardness (R_t) (in kbar)	Reference
B_4C	386	Kozhushko et al. (1987a-b)
SiC	220	Kozhushko et al. (1987a-b)
Al_2O_3	260	Kozhushko et al. (1987a-b)
Glass	144	Zlatin et al. (1988)
Quartz	100	Kobylkin et al. (1988)
7075 Al	26.5	Zlatin et al. (1989)
Ti-6Al-4V	35.5	Zlatin et al. (1989)

The significance of the Soviet results is not that Soviet researchers have made ultra strong ceramics, but rather that they have verified their concept that, when u is greater than C_F, strength is greatly enhanced. The very high observed R_t values have led to a number of Soviet theoretical studies considering what strength of ceramics is ultimately possible.

Western scientists have noted that their measured values of R_t are lower than theory would predict.[9] Soviet values have been much closer to theoretical values, substantiating their failure wave concept. In particular, R_t is similar to Hugoniot elastic limit (HEL) values (Kozhushko et al., 1987). Several researchers (including workers at the Ioffe Physical Technical Institute, who traditionally publish in penetration mechanics) have made attempts to calculate theoretical strengths on the assumption that all of the atomic bonds must be ruptured.[10] Table II.2 gives derived values. Values of strength in Table II.2 are generally twice those of Table II.1, which has led to the supposition that only half the bonds break in these high-velocity penetration processes. Vlasova et al. (1988) gave the relation that $R_t = \frac{1}{2}\rho C_T^2$ (where ρ is target density, and C_T is target shear wave speed).

Table II.2
THEORETICAL STRENGTH OF CERAMICS

Material	Theoretical Strength (kbar)	Reference
B_4C	645	Kozhushko et al. (1987)
SiC	559	Kozhushko et al. (1987)
Al_2O_3	595	Kozhushko et al. (1987)
Glass	100	Zlatin et al. (1988)

Given the practical importance of the failure speed, one might think there would be attempts to measure it. However, except for very recent work by Kanel' et al. (1992), this seems not to be the case. The value of C_F for glass was about 2.5 km/s, which is about $0.5C_L$. Ioffe workers and others usually state that C_F is between $0.5C_L$ and $0.9C_T$. The reference cited for this is by V. M. Finkel' (1970), a book this panel

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[9] M. J. Forrestal and D.B. Longcope, "Target Strength of Ceramic Materials For High-Velocity Phenomena," *J. Appl. Phys.*, *67* (1990), 3669-3672.

[10] Kozhushko et al., 1987; Shevchenko et al., 1984; Izotov and Lazarev, 1985, 1989.

was unable to obtain. Galanov et al. (1989) emphasized the distinction between Eulerian and Lagrangian values of C_F. C_F normally connotes a Eulerian velocity with respect to a stationary observer), whereas N (often used by theoreticians) refers to a Lagrangian velocity (with respect to moving a medium). N is a more fundamental parameter. According to Galanov et al. (1989), $N = 0.6\ C_T$. It is noteworthy that Kanel' has collaborated with Western workers to measure failure wave speeds.[11] Some Soviet authors and Western authors identify the failure speed of ceramics with the maximum crack propagation velocity, which is the Rayleigh wave speed.

One finds derivations of penetration as a function of impact velocity in Soviet literature that run counter to Western ideas. Lazarev et al. (1986) from the Technical Ceramics Interbranch Research Center at the Kurnakov General and Inorganic Chemistry Institute (Moscow), for example, (at a British conference) presented a model that also appears in several other Russian papers. In what is apparently a discussion of long rod penetrators, they derived that for the case of $u > C_F$,

$$p = (\ln a)^{2/3}(\rho_r v_r^2/\rho v_l^2)^{1/3}$$

Here ρ_r and v_r are the rod density and velocity, ρv_l^2 is the Young's modulus of the target, and a is the target lattice parameter. Equations with a similar functional dependence of p on velocity (for example, 2/3 power) have been known for a long time in the West, but they are never applied to long rods, and they are not derived in terms of fundamental crystal properties. The derivation is based on the dubious assumption that average strain is proportional to projective length.[12] Kozhushko et al. (1987b) found fault with this derivation because it leaves out target inertia and concludes that penetration does not depend on penetrator length.

V. I. Kovtun and colleagues in Kiev take a more conventional approach, using Alekseyevskiy-Tate theory, but based on the strength of failed material (Galanov et al., 1989). However, here too failure waves play a key role; failure waves are used to estimate the interval until boundaries degrade the ceramic strength. This is more sophisticated than Western treatment of size effects. However, the derivations in this

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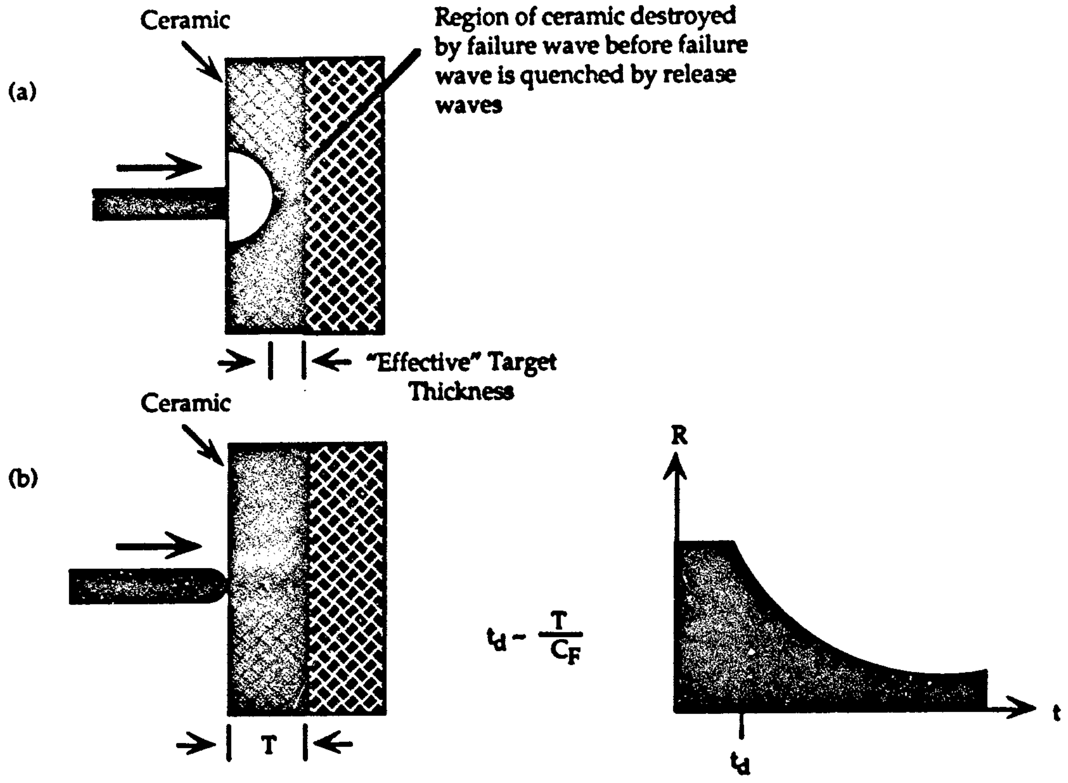
[11] S. J. Bless, N. S. Brar, Z. Rosenberg, and G. Kanel', "Failure Waves in Glass Bars and Plates," to be published in *J. Am. Cer. Soc.*, (1992).

[12] Strain should be assumed to be proportional to projectile diameter.

work contained many unjustified assumptions, and it was not a credible treatment of ceramic armor penetration. (Perhaps this paper is an export version.)

Figure II.1 is a summary of how failure waves can influence analysis of ceramic armor. The upper part represents the ideas of Zil'berbrand et al. (1989), and the lower part the concepts of Galanov et al. (1989). Failure wave concepts may be providing researchers in the former Soviet Union with a tool for understanding effects of the size and geometry on ceramic armor performance. This is a critical issue for which the West has not yet evolved an adequate analysis.



(a) Damage from impact shock.

(b) Resistance of thick tile decreases with time due to failure wave crossing tile.

Figure II.1
Sketches Illustrating Ways That Failure Waves
Affect Performance of Ceramic Armor

Kovtun et al. (1989) presented one of the few studies of penetration of ceramics at conventional ordnance velocities, using an ingenious radiography technique to trace the projectile material, and they obtained very original results. Their targets closely resembled those used in Western DOP (depth of penetration) experiments,[13] which suggests that they are very familiar with practical techniques for ceramic evaluation. These researchers concluded that SiC is melted at high pressure during penetration. Extensive melting of ceramics during penetration has not been considered by Western investigators.

b. Materials Under Investigation for Armor Applications

The number of different ceramics under investigation in the former Soviet Union appears to be less than in the West. Boron carbide (for example, Gogotsi et al., 1987a) and alumina are mentioned. There has also been work on armor properties of wet/dry sand (Dianov et al., 1976) and peat (Dianov et al., 1979). (Perhaps these materials were intended as a shock absorbing medium rather than primary armor.) However, the material of most interest seems to be self-bonded silicon carbide. Many papers on this material are written by investigators who have also published in ballistics.[14] This material was also considered as armor against shaped-charge jets (Vlasova et al., 1988).

Several Soviet research publications on this subject were reviewed by Robert Palia, who works at Carborundum, a leading US producer of armor-grade SiC. He reported that the Soviet material appears to correspond to a product commercially produced by Carborundum since the 1950s, which consists of SiC with excess silicon.[15] The commercial designation is KT silicon carbide. Better armor performance was found to result from single phase material, the current Carborundum armor product (designated Hexoloy).

Devitrified glass was discussed by Zil'berbrand et al. (1989). Penetration of pure silicon was described by Kovtun et al. (1989—discussed above). The Materials

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[13] For example, C. E. Anderson and B. L. Morris, "The Ballistic Performance of Confined Al_2O_3 Ceramic Tiles," to appear *Int'l. J. Impact Engng.*, 1992.

[14] For example, Vlasova et al., 1985; Bushlov et al., 1988; Kovtun and Timofeyeva, 1988; and Vlasova et al., 1988.

[15] R. Palia, Letter to S. Bless on subject of "Reaction Bonded SiC—Soviet Papers", 3 Jan 1992.

Science Institute in Kiev has been especially active, reporting on B_4C and B_4C-Al (Gogotsi et al., 1986, 1987b). Soviet researchers have been world leaders in dynamic synthesis, so it is not surprising that they have conducted a great deal of work on shock wave synthesis of ceramics, and armor seems to be an application. Shock sintered BN has been discussed by Vlasova et al. (1988) and Kovtun and Trefilov (1988). There is no compelling evidence that practical production processes have been developed.

There has been a great deal of Soviet research on porous materials, especially metals (for example, Trunin et al., 1989; Stepanov et al., 1988). There have been relatively few treatments of porous ceramics (for example, Osipov et al., 1989; Bubnov et al., 1986; Balankin 1989d). Balankin found that for all penetration modes there is less penetration by jets into porous materials than corresponding voidless material. Porous ceramics, may also provide a means of lowering C_F without much affecting strength, and it is reasonable to suppose that this has been a subject of investigation in the former Soviet Union.

2. Metallic Armor

a. General

The research reviewed under metallic armors includes two types of papers, those that deal with dynamic properties of materials, and those dealing explicitly with penetration phenomena. In general, Soviet writers on metallic armor have often cited classic US references from the 1960s, such as papers by Recht and Backman. It is noteworthy that (with very few exceptions) Soviet researchers have not discussed penetration by long rod projectiles at ordnance velocities, even though this is the fielded threat. Evidently all long rod experiments were classified.

b. Penetration of Thin Plates

There are two main penetration modes of thin plates, plugging and petaling. Plugging is generally the more important; in this process, the projectile pushes a slug of target material out the back of the plate, thereby opening a channel through which it can pass.

There have been many papers on this subject, especially from the Strength Problems Institute in Ukraine. Most of these papers are relatively pedestrian. The use of a ballistic pendulum is common.[16] The treatments in these papers are very similar to rather old work in the West.

More noteworthy has been work by Kanel's group (Sugak et al., 1987). G. I. Kanel' is a leading researcher on impact behavior; he has presented calculations of plugging and concluded that shear localization is due to void softening, not temperature-driven shear localization (which is the most accepted explanation of plug formation in the West). A few Soviet authors have discussed shear band models (for example, Meshcheryakov et al., 1988; Tetenov, 1990). Tetenov (1990) lamented the fact that shear band study has been relatively neglected in the Soviet Union.

A. Ya. Sagomonyan in his book (1988) reviewed many solutions, including rigid blunt punches, added mass models, effects of shock waves, and many projectile behavior modes including elastic-plastic. His emphasis is on analytical solutions. The text seems to imply sometimes that these analyses have been used in developing new projectiles. The main value of this reference is as a source book, not originality.

One interesting solution in Sagomonyan's book is for hollow projectiles filled with liquid. This presumably corresponds to a chemical shell.

c. Penetration of Thick Targets

Much of Soviet treatment of thick metals has also been based on modified Alekseyevskiy-Tate theory. (See Section II.C.1.a for a discussion of this theory.) It is curious that many researchers describe this concept as if it were a controversial modification of conventional hydrodynamic theory (which describes penetration of shaped-charge jets by ignoring strength), though it seems to have been the standard Soviet model. In some ways, Soviet researchers have taken this model farther than those in the West. A summary of the modern version of this theory, which even Western workers may find useful, was presented by Sagomonyan (1974), including a full discussion of the supersonic penetration case.

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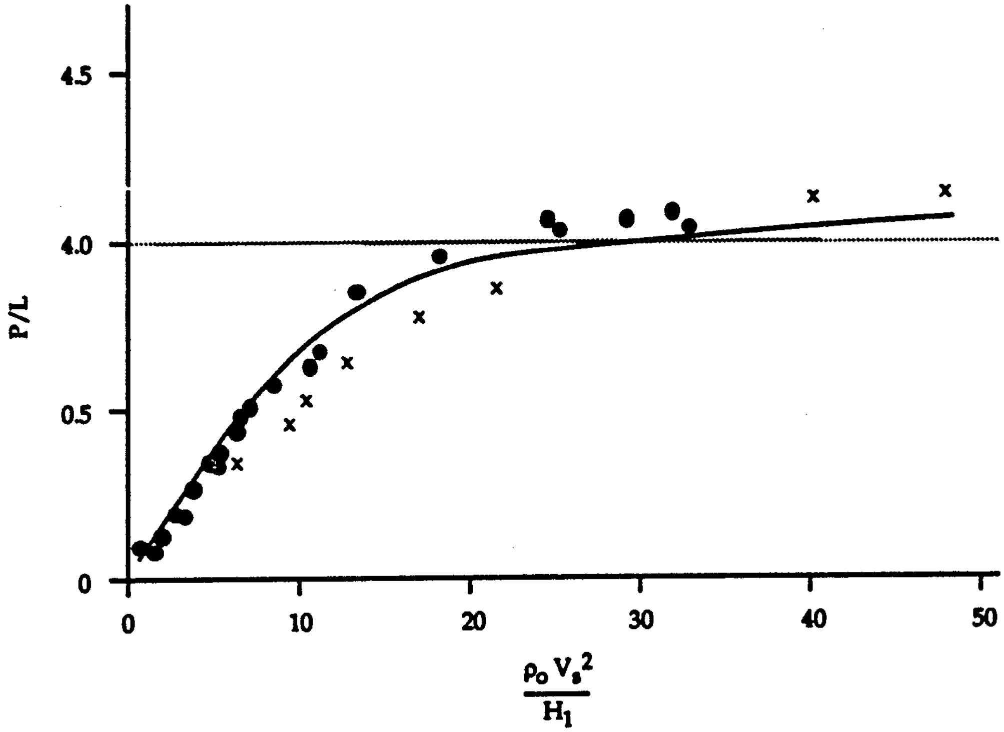
[16] For example, Astanin and Stepanov, 1983; Stepanov and Avetov, 1986; Stepanov et al., 1988; Stepanov and Safarov, 1988; Sagomonyan, 1988.

In work of Zil'berbrand et al. (1989) from the Ioffe Physical Technical Institute, for example, the Tate model for penetration thresholds has been used. In the work by Zlatin et al. (1989), Ioffe researchers presented some R_t values for metals: 26.5 kbar for an aluminum that seems to correspond to 7075T6, and 35.5 kbar for Ti-6Al-4V; these are similar to US values. Yevstrop'yev-Kudrevatyy et al. (1990) presented a very elegant paper showing how penetration scales as $\rho v^2/R_t$; this is probably generally believed in the West, but has not been nicely shown in a publication. Figure II.2 illustrates some data from this paper.[17]



Circles are copper and steel, crosses are aluminum.

Figure II.2

Data from Yevstrop'yev-Kudrevatyy et al. (1990—cited from Kozorezov and Mirkin, 1967) Showing How Penetration of Tubes Varies with Impact Velocity

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[17] Note: Western data for long rods were used by these authors, presumably because Soviet data were classified.

A remarkable catalog of penetration phenomena of shaped-charge jets or rods was presented by Balankin (1989d). A viscous flow term was added to the conventional Tate equation that takes the form of viscosity times average radial strain rate, thus taking into account strain rate effects and penetrator diameter effects. This model of diameter effects could be an important addition to the usual Tate formulation. In addition to discussion of the usual cases of subsonic and supersonic penetration in the target (for which Balankin derived a simpler formula than the one usually used), he also discussed cases in which the consumption velocity of the penetrator exceeds the sound speed in the penetrator, and turbulent penetration in the target. He concluded that the first corresponds to melting of the penetrator at the impact zone.

Cavity expansion models similar to those developed by Forrestal in the West,[18] were thoroughly developed in Sagomonyan's book (1988—which is an extension of his 1974 book) and in the paper by Stepanov and Safarov (1990). In some areas they seem to lead the Western work, but in most others they are less advanced. One new treatment was that of layered elastic/plastic materials; this may represent an attempt to model penetration of composites.

Kovtun and coworkers (Kovtun et al., 1989; Kovtun and Mazanko, 1988) have developed an interesting autoradiography technique with some surprising observations. This was an experimental technique to track movement of material in targets penetrated by long rods or shaped-charge jets. It was found that some target material appears to move into the target with the penetrator. This runs counter to the conventional wisdom, which is that target material is simply pushed out of the way by the penetrator.

I. P. Spirikhin (1989) from the Moscow Power Institute also discussed supersonic penetration of metal targets. Soviet interest in this subject is surprising, since military projectiles (even shaped-charge jets) do not normally penetrate metals supersonically. If the former Soviets have supersonic penetrators, then they are using launch schemes quite different from those used in the West. (There has been some Western

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[18] M. J. Forrestal, V. K. Juk, and N. S. Brar, "Perforation of Aluminum Armor Plates with Conical-Nose Projectiles," *Mech. of Materials*, 10(1990), 97-105.

work on supersonic penetration, but it is generally perceived as of academic interest only.)

d. Ricochet

There are very few Soviet papers on ricochet, but there are not many in the Western literature either. Bulantsev et al. (1985) presented a numerical treatment and data for ricochet of spheres. Khorev et al. (1985) have treated ricochet of rods by a numerical technique that looks similar to Western treatments of this problem.

e. Properties That Affect Penetration

Extensive Soviet publications on dynamic properties of materials seem to have been motivated by a desire to understand ballistic penetration phenomena. This work has generally been of high quality and similar to material published in the West. The two most active research teams are at Chernogolovka (led by Kanel') and S. A. Novikov, A. G. Ivanov, V. K. Golubev, and coworkers at the Experimental Physics All-Union Scientific Research Institute in Sarov (formerly Arzamas-16).

Both of these groups have devoted a great deal of attention to spall failure, but they have used different techniques and even definitions. Kanel' and his associates have derived spall strengths from pull back signals, which tends to give damage threshold values. Novikov and his coworkers have based their analysis on recovery. Novikov's team seems to have been mainly interested in EFPs (explosively formed projectiles), judging by the materials investigated and the importance of high temperature in their work. Perhaps they have felt the more conservative strength derived from recovery is more appropriate to describing failure of these types of projectiles.

Spall studies that are of special interest and merit include the following: aluminum and rate dependence (Meshcheryakov and Divakov, 1986), magnesium-lithium (Golubev and Sobolev, 1991), titanium (Kanel' et al., 1986; Golubev et al., 1985a) molybdenum (Golubev et al., 1985a), nickel (Golubev et al., 1985a), mild steel (Golubev et al., 1985b), tantalum (Golubev et al., 1988), Ta10%W (Golubev et al., 1988), and steel (Meshcheryakov et al., 1988). Most of these materials are being considered in the West for advanced penetrators or explosive warheads.

f. Signature

Researchers at the Ioffe Physical Technical Institute have been studying radiation associated with fracture. Abramova et al. (1989, 1990) studied radiation from spall. Note that Abramova et al. (1990) treated titanium; this may have been an attempt to obtain a signature from impact on advanced aircraft or missiles. There was sufficient light for "self light" photographs, and the spectra were recorded.

A topic on which there is considerable speculation, but almost no data, is charge separation in high-speed impact. The recent paper by Devyatkin (1990), in which he found the effect measurable but quite small, is thus a worthwhile contribution.

g. Superdeep Penetration and Anomalous Transport

Study of the phenomenon called superdeep penetration has been perhaps the most curious aspect of penetration mechanics in the former Soviet Union. This is an intriguing subject that may have important consequences, and which has not been noted or studied in the West.

Conventional experience is that high-speed projectiles, impacting at 2 to 3 km/s are capable of penetrating several diameters into structural metals. At this speed, the projectile is generally destroyed, and the penetration consists of a bowl-shaped crater in the target. Superdeep penetration is a startling departure from this experience. Small particles are able to penetrate many hundreds of diameters, the particles are found practically undeformed in the target, and the penetration channel closes behind the projectile in the target.

Superdeep penetration has been described, for example, in work by Buravova(1989), Bakhrakh et al. (1991), Al'tshuler et al. (1989), and Andilevko et al. (1988). Workers in this field have included L. V. Al'tshuler, the dean of Soviet shock physicists, who received a prize in 1991 from the US Physical Society for his pioneering work. His participation would seem to certify this as a genuine phenomenon occupying some of the best talent in the former Soviet Union.

The phenomenon of superdeep penetration has only been reported for very small impactors, usually less that 0.1-mm diameter, and typically 0.01-mm diameter. Particles are launched in dense clouds, apparently by explosives. The multiple impact scenario seems important for at least two reasons: only a small percentage of particles is able to engage in superdeep penetration, and the multiple shock environment may aid the process. Particles have usually been ceramics, but silicon has also been used. Targets are usually metals, such as steel, copper, or titanium. Superdeep penetration is also very material dependent, in that only certain combinations of particles and substrates will produce this phenomenon (see, for example, Andilevko et al., 1988).

The motivation for Soviet research in this subject is not clear. Applications could be commercial (for surface properties), military (assuming the Soviet Union possessed a warhead capable of producing such fragments), or for spacecraft (but the density of impacts seems much too high for normal orbital debris). One may also speculate that the mechanism of superdeep penetration, if understood, might be made to operate on a macroscale. Thus, perhaps the Soviet interest in superdeep penetration might have been intended as a precursor to development of radically new military technologies. (See also the discussion of this topic in Chapter V.)

The subject of anomalous transport is similar to superdeep penetration, in that it involves surprising movement of very small particles, and has not been noticed by Western investigators. There are several Soviet references to this phenomenon, one of which is by Alekseyevskiy (et al., 1989), a very prestigious worker in penetration mechanics, and another is by Gluzman and Psakh'e (1989). Anomalous transport involves the movement of radioactive tracer particles by shock waves. It is not clear that this phenomenon has military applications, except that it suggests that, under some conditions, shock deformation departs considerably from our usual conceptual models.

h. Spall and Spall Suppression

As in the United States, there have been many Soviet studies of spall criteria in metals. Soviet application studies have often taken a different approach than is common in United States.

There are Soviet papers on crack growth criteria that are similar to the work of Grady in the United States.[19] The paper by Fadeyenko (1977) is an example of this type of Soviet work.

Spall suppression by porous materials was studied by Belov et al. (1988), and spall suppression seems to have also been the motive for the study of porous iron by Aptukov et al. (1988). The loading source in the work by Belov et al. (1988) was explosive. This technology for spall suppression has not been seriously considered in the United States.

According to Kostyukov (1980) and Gel'fand et al. (1987), amplification of shocks by porous layers is also possible. In this case, the porous material seems to be on the outside of a structure that is subjected to blast load.

Front surface spall was studied by A. N. Dremin, one of the leading shock physicists in Russia, and co-workers (1986). The application seems to be targets struck by EFP type projectiles. A finite element code was used. While the particular results are not especially noteworthy, it is noteworthy that such a relatively prosaic problem occupied the attention of top research scientists, which may indicate that advanced Soviet technology in this area exists.

Khorev and Gorel'skiy (1983) discussed the penetration of spall caps by projectiles. They used a finite difference calculation, and their success in matching data indicates considerable computational ability, as well as interest in spall formation in light armored vehicles struck by high-velocity fragments.

3. Composite Armor

Very few Soviet papers on this important subject were identified, even though we know the Soviets have fabricated armor using aramid fibers.[20] The main research team is at the Ioffe Physical Technical Institute, and these are the same people who work on ceramic armor, so evidently ceramic/composite armor must be a

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[19] D. E. Grady, "Local Inertial Effects in Dynamic Fragmentation," *J. Appl. Phys.*, 53(1982), 322-325.

[20] S. J. Hanchak has reported in a private communication that the University of Dayton Research Institute had tested a Soviet aramid armor that was offered as a sample to a US armor company in November 1991.

technology of interest to the Russians (as it is to the West). Bagdoyev and Vantsyan (1989) have discussed drilling composites. Peschanskaya et al. (1984) and Zlatin et al. (1983) have discussed dynamic properties of polymers, including spall of PMMA.

4. Electromagnetic Armor

There appears to be considerable interest in the effects of electric currents and magnetic fields on high-speed deformation of metals in the former Soviet Union, and there is probably more published work than can be found in Western literature. The application is presumably electromagnetic armors.

Armor research teams at the Ioffe Physical Technical Institute have been studying exploding wires for a long time, starting in the 1960s (Abramova et al., 1966) and continuing through the 1970s (Abramova et al., 1975), but there was not much in the 1980s. (A similar pattern can be found at the US Army Ballistic Research Laboratory.) This work is probably not armor related.

Electroplasticity has been studied extensively—a topic not discussed in the West. A group at Leningrad State University (Bagdoyev and Vantsyan, 1988; Troitskiy et al., 1987) reported two-fold increase in plastic properties when an electric current is present: there is decreased penetration in the presence of a current, apparently due to blunting of the penetrator, but this effect was not observed for tungsten alloy penetrators (Bagdoyev and Vantsyan, 1988). The current flow in these tests was from the penetrator into the target. Troitskiy et al. (1987), from a tungsten research group, separately measured the effects of electric currents on the properties of tungsten. The strain needed to induce failure was increased considerably. Note that this latter work has obvious manufacturing implications, and may not be intended for military applications.

Sagomonyan's book on penetration mechanics (1988) treats effects of current on penetration and mentions that there has been considerable research on this topic. Quoting Bagdoyev and Vantsyan (1988), he says penetration reductions are possible up to 60 percent for 100 kA at 200 V. The application seems to be armor piercing bullets striking aluminum. The mechanism is reduced strength of the penetrator. The current is localized in the contact region. Sagomonyan also refers to the pinch effect as being important. Since pinch effects only matter in liquids, this implies that this technique is also used against shaped-charge jets.

Breakup of shaped-charge jets by currents was explicitly discussed by Yanevich et al. (1990). This paper is on general breakup criteria. The paper states that the jet breakup mechanism is not pinch effect, as would occur in a liquid; the actual mechanism is arcing between segments, leading to melting. In the view of these researchers, segmentation of the jet starts very early or is present initially. (This opinion is heretical in the West.) References cited by Yanevich et al. (1990) indicate that this work is very recent.

Considering this body of work, it appears that researchers in the former Soviet Union have had a dedicated program in electromagnetic armor for some time. It would be reasonable to expect that if electromagnetic armor is feasible, the Soviet Union would have developed this technology.

5. Experimental Techniques

Soviet researchers have employed many advanced experimental techniques that are on a par with those available in the best Western laboratories. Galanov et al. (1989) reported techniques to visualize damage. The bar impact configuration to study spall, only recently developed in the West,[21] has been in use in the former Soviet Union for some time (Zlatin et al., 1983). Dynamic holography has been developed at the Ioffe Physical Technical Institute (Kamshilin et al., 1990). Manganin gage technology is quite mature (Bat'kov et al., 1988; Kanel' et al., 1992). VISAR (diffused laser interferometry) technology is also well established, and, in the work by Divakov et al. (1987) and Atroshenko et al. (1990), has been extended to very small spot sizes for making unique measurements of microdeformation mechanics. Free surface velocity has also been measured by Novikov et al. (1986) using an inductive device. A sub-nanosecond streak camera was employed by Ludikov et al. (1990). A clever autoradiography technique to trace movement of target tracers was used by Kovtun and Mazanko (1988) and Kovtun et al. (1989). Many studies of extreme

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[21] N. S. Brar and S. J. Bless, "Dynamic Fracture and Failure Mechanisms of Ceramic Bars," *Int'l Conf. on Shock-Wave and High-Strain Rate Phenomena in Materials (Explomet 90), San Diego, 12-17 Aug 1990.*

hypervelocity impact (> 12 km/s), such as that by Balankin (1988c), indicate a Soviet capability to launch very small particles to orbital velocities (using electrostatic or plasma accelerators).

About 10 years ago, the Moscow Power Institute published an intriguing technique to accelerate particles up to millimeter-size to extremely high velocity by using an electrostatic device (Grigor'yev et al., 1981; Sinkevich et al., 1981). In this technique, particles were produced by allowing a liquid jet to break up into uniform drops. These particles were charged and then accelerated by electrostatic fields. Velocities of up to 100 km/s were claimed to be feasible with diameters up to 10 mm. If such beams could really be produced, they might have great importance for high-velocity impact studies and as a beam weapon (Askar'yan et al., 1982). However, clearly, the ratio of charge to mass must be less for large particles, making it more difficult to accelerate macroparticles. The Soviet researchers apparently perfected production of the initial particle stream, but were speculating on the feasibility of acceleration. This panel found no evidence that this technique was actually developed.

6. Reactive Materials and Explosive Technology

The subjects of reactive materials, shaped-charge jets, and other explosive technologies are marginal to this assessment. However, since Soviet researchers have occupied leadership positions in several of these fields, it was considered worthwhile to present a brief picture of these fields in Table II.3.

The most prolific Russian researcher currently in shaped-charge jet formation, explosion phenomena, and penetration is A. S. Balankin, at the Moscow Engineering Physics Institute, whose work is extraordinarily provocative and original. Unfortunately, it is also very difficult to evaluate, because his often bold assertions are not supported by data or detailed analysis. Balankin may be a genius, but his published work is insufficient to establish this.

7. Penetrator Design

No Soviet publications dealt explicitly with penetrator design. However, a few papers at Moscow State University were obviously motivated by this subject. These mainly concerned rigid body penetration by various shape projectiles. Wedges were treated by Gonor (1986a) and needle noses by Gonor and Poruchikov (1989). Star-shaped penetrators have also been investigated (Gonor, 1986b; Ostapenko, 1989). Slab penetrators were also discussed by Yevstrop'yev-Kudrevatyy et al. (1990). These are elegant applications of potential flow theory, and it is reasonable to suppose that they were motivated by unpublished experimental work, in which the designs resulted in improved performance.

Table II.3
BRIEF SUMMARY OF SOVIET WORK ON EXPLOSIVES AND EXPLOSIVE DEVICES

Subject	References	Principal Findings	Possible Significance
Thermal explosions from high-velocity impact.	Balankin et al. (1989a); Zlatin and Kozhushko (1982)	Over 10 km/s many particles explode on impact and cause very little penetration.	Orbital debris?
Scaling of explosive phenomena and innovative models for explosive initiation	Balankin et al. (1989, 1989a); Balankin (1989b)	There is an intrinsic scale to explosive events.	Improved reactive armor; improved explosives
Shock induced chemical reactions	Batsanov and Gur'yev (1987); Batsanov et al. (1986); Gluzman and Psakh'e (1989)	Reactions seen in SnS. Not clear if the application is armor.	New types of armor?
Penetration mechanics of shaped-charge jet	Krasnoshchekov et al. (1990); Balankin (1989d); Kinelovskiy and Mayevskiy (1988); Kovtun and Mazanko (1988)	An inversion technique has been developed to find contributions of each jet element. Part of the target moves with the jet.	Improved armor
Ultra dispersion of particles using high explosives	Beloshapko et al. (1990)	50 nm oxide particles have been dispersed.	?

Table II.3
BRIEF SUMMARY OF SOVIET WORK ON EXPLOSIVES AND EXPLOSIVE DEVICES
(cont'd.)

Subject	References	Principal Findings	Possible Significance
Shaped-charge jet stability	Yanevich and Balankin (1990); Krasnoshchekov et al. (1990); Balankin (1988b)	It has been shown that jets are not liquid, but crystalline. Anomalous ductility seen in jets due to recrystallization. Cracks are present initially so segmentation is not due to instabilities. Some anomalies explained by special case where velocity exceeds C_F.	Improved explosive warheads
Hemispherical-shaped charges	Kinelovskiy and Mayevskiy (1988)	It is clear that these devices are well known.	Improved explosive warheads
Explosively formed penetrators	Merzhiyevskiy and Resnyanskiy (1987); Merzhiyevskiy et al. (1986); Balankin (1988b); Dremin et al. (1986)	It is clear from these numerical studies and many property studies that this technology is actively pursued.	Fly-over warheads.
Explosive loading of structures	Abukumov et al. (1991)	This is undoubtedly a big field; just one recent reference is noted.	Structure and vehicle design for overpressure
Impact detonation of bulk explosive	Fortova et al. (1979); Kobylkin et al. (1988)	Explosive initiation criteria for calculations, including confined explosives.	Sensitivity of explosive devices.
Impact detonation of thin explosive layers	Dubovik (1988); Bobolev et al. (1982); Amosov et al. (1972); Dubovik and Lisanov (1985)	Soviet work on impact detonation has placed more emphasis on shear bands and friction than most US studies.	Design of explosive devices.

There has been much interest in tantalum-tungsten alloys (Golubev et al., 1988) and sintered and tungsten-rhenium (Podrezov et al., 1987). These alloys have also been considered by Western researchers. As in the West, there has apparently been little interest in brittle penetrators, except the work by Gridneva et al. (1977), who discussed glass rods.

D. PROJECTIONS FOR THE FUTURE

Several of the research areas assessed in this chapter have potential for weaponization. Perhaps a clue to this process would be a drop in publications describing basic research. The subject areas that could be tracked in this regard are the following:

- Work on high-speed penetration of ceramics.
- Work by Balankin on shaped-charge jet stability and penetration mechanics.
- Work on properties of porous ceramics, especially measurements of strength and of failure speeds of these materials.
- Work on superdeep penetration, especially any indication that this could be made to operate on a macro scale.
- Work on shock-induced chemical reactions.
- Work on porous materials for spall suppression.
- Work on electromagnetic armor.
- Work on macroscopic particle beams.
- Work on non-circular cross section projectiles.

Table II.4 compares publications relevant to penetration mechanics experiments at ordnance velocities in the former Soviet Union with those in the United States.

Table II.4
COMPARISON OF SOVIET AND US PUBLICATIONS IN PENETRATION MECHANICS AT ORDNANCE VELOCITIES

Technology	Former Soviet Union	United States
Penetration mechanics of ceramics	++	+ (Note 1)
Porous ceramics (as armor)	+	
Metallic penetration mechanics/armor	+	+
Dynamic property measurements	++	+
Superdeep penetration	++	(Note 2)
Explosively formed penetrators	+	+
Penetrator materials	+	+
Long rods at ordnance velocities	(Note 1)	+
Hypervelocity penetration of rods	+	+
Shock-induced reactions	+	+
Instrumentation	+	++

Note 1: Publications suppressed by classification.
Note 2: No publications.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table II.5 provides the names of key researchers in penetration mechanics experiments at ordnance velocities in the former Soviet Union and its successor states and the research facilities with which they are affiliated.

Table II.5
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—PENETRATION MECHANICS EXPERIMENTS AT ORDNANCE VELOCITIES

Applied Mathematics & Mechanics Institute,
Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)

A. I. Korneyev
V. A. Gorel'skiy
I. Ye. Khorev (now at Chernogolovka)

Chemistry & Mechanics Central Scientific Research Institute, Moscow (Russia)

Yu. I. Krasnoshchekov

Engineering Physics Institute, Moscow (Russia)

A. S. Balankin

Experimental Physics All-Union Scientific Research Institute, Arzamas-16/Sarov (Russia)

S. A. Novikov
V. K. Golubev

General & Inorganic Chemistry Institute im. N. S. Kurnakov,
USSR/Russian Academy of Sciences, Moscow (Russia)

A. D. Izotov
V. B. Lazarev
I. I. Rykova

High-Temperature s Institute, Chernogolovka (Russia)

A. N. Dremin
G. I. Kanel'
V I. Fortov
I. Ye. Khorev
S. G. Sugak

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch,
USSR/Russian[22] Academy of Sciences, Novosibirsk (Russia)

L. A. Merzhiyevskiy
A. D. Resnyanskiy

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[22] At the end of 1991, the USSR Academy of Sciences changed to the Russian Academy of Sciences, the name it used before June 1925.

Table II.5

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—PENETRATION MECHANICS EXPERIMENTS AT ORDNANCE VELOCITIES

(cont'd.)

Machine Science State Scientific Research Institute im. A. A. Blagonravov, Gor'kiy/Nizhniy Novgorod[23] Branch (Russia)

V. N. Perevezentsev

Materials Science Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)

B. A. Galanov
V. I. Kovtun
O. N. Grigor'yev
V. N. Ostapenko

Mining Institute, Novosibirsk (Russia)

Ye. V. Tetenov

Moscow State University im. M. V. Lomonosov, Moscow (Russia)

A. L. Gonor
A. Ya. Sagomonyan

Physical Technical Institute im. A. F. Ioffe, USSR/Russian Academy of Sciences, Leningrad/St. Petersburg

N. A. Zlatin (deceased)
Ye. L. Zil'berbrand
A. A. Kozhushko
V. A. Stepanov
V. B. Lazarev
N. N. Peschanskaya
V. V. Kostin
G. S. Pugachev
I. I. Rykova
A. D. Izotov

Powder Metallurgy Scientific-Industrial Association (Belarus)

S. K. Andilevko

Strength Problems Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)

G. V. Stepanov
V. N. Gurskiy
V. V. Kharchenko
A. M. Ul'chenko

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[23] Gor'kiy recently resumed its historical name, Nizhniy Novgorod.

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CHAPTER II: PENETRATION MECHANICS EXPERIMENTS AT ORDNANCE VELOCITIES
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CHAPTER III
HYPERVELOCITY IMPACT CAPABILITIES

A. SUMMARY

Research in the former Soviet Union in hypervelocity impact research has been vigorously pursued on several fronts. Several institutions have been actively developing explosive driver techniques for launching solid projectiles to ultra-high velocities. These techniques have been used to obtain experimental data on the dynamic equation of state of vapors and plasmas produced by shock loading, research that is presently unparalleled at Western laboratories. The data obtained with this method are the most complete available and have been used by Soviet investigators to confirm theoretical predictions and to provide validation of theoretical models used in computer analysis of hypervelocity impact events. Recent published Soviet research has reflected a strong trend in the use of numerical simulations for analyzing hypervelocity impact phenomena and in the use of computer analysis for optimizing experimental techniques.

Based on the present review of Soviet research, certain facilities have been prominent in hypervelocity impact studies. Foremost has been the research group at Chernogolovka. The intellectual leader of this group is Vladimir Fortov, who directs the Physical Hydrodynamics Division at the Chemical Physics Institute, Chernogolovka. Fortov is renowned for his basic studies of plasma physics and of high-pressure equations of state. This group has been closely aligned with research activities at the High Temperatures Institute, also directed by Fortov. Fortov's group has developed a capability using explosive launchers to achieve the highest velocity presently available for routine equation-of-state studies in the laboratory. Other key investigators in hypervelocity research under the direction of Fortov include S. I. Anisimov, V. A. Agureykin, and Ye. F. Lebedev. This group also has a strong capability in computational modeling.

A second major group playing a leading role in hypervelocity physics has been at the Hydrodynamics Institute in Novosibirsk. The technical leaders of this group are L. A. Merzhiyevskiy and G. A. Shvetsov. Their principal interests are in ballistic impact experimentation, jetting, and railgun development.

Another major research group has been at the Ioffe Physical Technical Institute, Leningrad, under G. I. Mishin. Their main interest is in ballistic testing dynamic and in dynamic material property measurements.

There have been several other groups with limited visibility in hypervelocity impact research. Included among these are those at Moscow State University with V. I. Kondaurov, Tomsk State University with I. Ye. Khorev and A. I. Korneyev, and the Landau Theoretical Physics Institute with A. B. Konstantinov and A. V. Bushman.

Observable trends in Soviet hypervelocity research have included (1) continued improvement of explosive techniques for generating high velocity; (2) basic studies of railgun technology to improve operational performance; (3) increased reliance on computational modeling to design experiments and interpret phenomena; and (4) the investigation of new approaches such as particle beams and lasers to augment hypervelocity impact research.

Significant collaborations have been established between groups at different institutions to enable the solution of difficult problems, such as the design of debris shields for the Vega spacecraft used to probe Halley's comet.

B. INTRODUCTION

This Chapter describes Soviet capabilities involved with the development and application of hypervelocity impact techniques. For the purpose of this discussion, hypervelocity refers to the velocity range where impact effects are governed primarily by hydrodynamic properties of materials. Typically, these effects are dominant for impact velocities exceeding 4 to 5 km/s. Hypervelocity impact research is also considered to include both ballistics work and high-pressure equation-of-state studies and encompasses a broad range of material effects, as illustrated in Figure III.1.

. Soviet interest and involvement in hypervelocity date back to the late 1950s, and hypervelocity impact research has continued as a principal activity. Soviet satellites launched in September and October 1959 were instrumented to detect meteoric particle impact on the spacecraft (Nazarova, 1961a-b) and were successful in recording the impact momenta and impact rate of high-velocity particles at various elevations above the Earth. Following these observations, major experimental efforts were directed towards characterizing hypervelocity impact phenomena[1] with micron-sized particles to velocities of about 30 km/s, and later to about 10 km/s with gram-size projectiles using light-gas guns (Merzhiyevskiy and Fadeyenko, 1973). The development of capabilities for studying hypervelocity impact phenomena at 30 km/s was far ahead of efforts elsewhere.

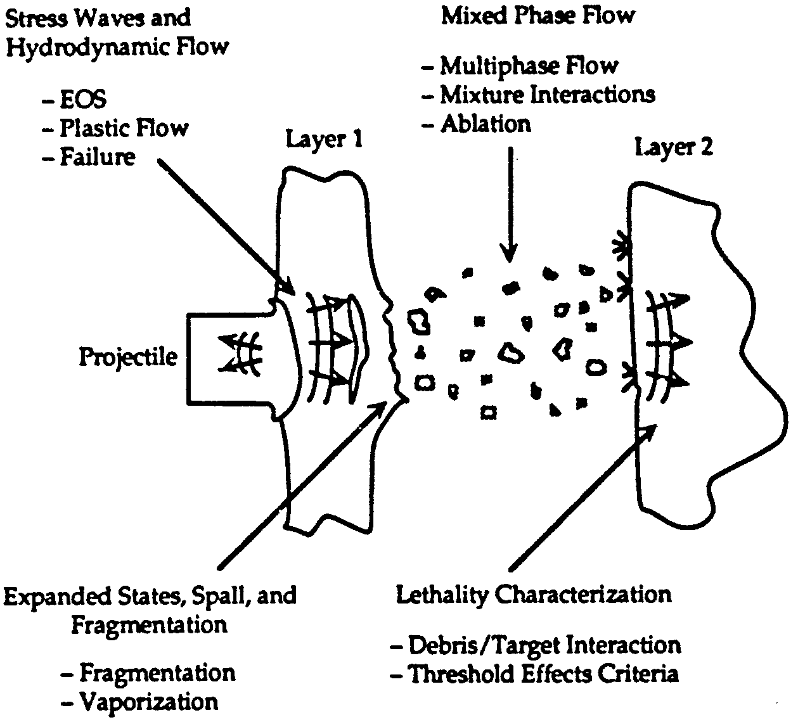

Figure III.1

Phenomena Occurring in Hypervelocity Impact Events

Several important hypervelocity impact phenomena were studied in the early Soviet experiments. These included (1) the study of how vaporization influences impact effects (Rusakov, 1969, 1975); (2) the importance of momentum enhancement (Rusakov and Lebedev, 1968); (3) the morphology of impact craters (Rusakov and

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[1] See the collection of papers by Rusakov in the reference section at the end of this chapter.

Shaydullin, 1979); and (4) the relationship of cratering to impacting particle energy. It was observed that the impact velocity has a pronounced influence on crater and penetration at these velocities. The database developed by Rusakov and his colleagues was used to develop analytic relations for impact cratering (Stanyukovich, 1961a) and for particle penetration in the velocity range of 50 to 100 km/s (Lavrent'yev, 1961).

Rusakov's method of launching particles to 30 km/s has been used as recently as 1986, but there have been no active programs to improve it, and it appears that other techniques, such as electrostatic acceleration, are presently being used (Abramov, 1991; Semenov, 1991) to launch small particles to velocities exceeding 40 km/s.

The early Soviet experimental studies in hypervelocity were centered at laboratories involved in weapon programs, notably at the Technical Physics All-Union Scientific Research Institute in Chelyabinsk and the Lavrent'yev Hydrodynamics Institute in Novosibirsk. Several scientists at these institutes, particularly M. M. Rusakov, L. A. Merzhiyevskiy, and V. M. Titov, have continued their involvement in hypervelocity studies for over 20 years. Additional efforts were later established at several other institutions, which led to the broadening of research into advanced launcher techniques and the incorporation of modern computing techniques.

Recent Soviet activities in hypervelocity have spanned a wide range of experimental capabilities, and include the use of standard light gas guns, the development of advanced electromagnetic launchers, the development of staged explosive devices for launching plates to 16 km/s, and the use of space programs, such as the Vega space probe, for performing unique hypervelocity impact experiments.

An important component of Soviet development of hypervelocity launcher technologies has been the development of electromagnetic launchers, notably railguns. Research in railgun development has been focused in recent years at three facilities, with a goal of achieving projectile velocities of 10 km/s or greater. The total effort appears to have been equivalent or perhaps slightly larger than railgun programs in the United States or other countries. The railguns discussed in the published literature are prototype systems with purported objectives of understanding plasma physics, and with the ultimate goal of resolving operational problems presently limiting railgun performance. These programs have reported achieving projectile velocities of 7.1 km/s (Drobyshevskiy et al., 1990) and 7.5 km/s (Shvetsov, 1990), which are higher than confirmed velocities achieved in the United States, but equivalent to recent results reported by Japanese investigators.

In another area, Soviet investigators have perfected the use of staged explosives and modified shaped-charge jets for launching small projectiles to velocities of 16 km/s (Anisimov et al., 1986; Avrorin et al., 1990). These experiments have been used primarily for equation-of-state studies of vapors and partially ionized plasmas (Al'tshuler et al., 1980; Avrorin et al., 1990; Ageyev et al., 1988). Soviet investigators have generated an impressive database related to the vapor state of several metals with these techniques and are undisputed leaders in this area.

Recent hypervelocity activities in the former Soviet Union have also involved considerable development in numerical analysis methods (Avrorin et al., 1990). The use of numerical analysis has appeared as an increasingly important capability in a variety of Soviet programs. An observable trend is a definite emphasis on the use of computing methods to design complex experiments. Examples include design of the Vega debris shield and of on-board experimental diagnostics for performing impact experiments at 80 km/s (Anisimov et al., 1984; Avrorin et al., 1990); the prediction of transient damage to metallic plates produced by proton beams (Leshkevich et al., 1989); and the design[2] of improved explosive Mach shock wave generators for launching flyer plates to velocities exceeding 16 km/s (Avrorin et al., 1990).

Recent publications indicate that several programs involving numerical simulation have been accomplished through research collaborations at several institutions. For example, computer simulations of the impact experiments for the Vega flyby of Halley's comet involved investigators from the Chemical Physics Institute, Chernogolovka, who are knowledgeable in equation-of-state studies, and researchers at the Applied Physics Institute, Novosibirsk, who have developed computer capabilities for numerical simulations (Agureykin et al., 1984).

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[2] Walter Herrmann, Trip Report on Travel to the III Lavrent'yev Readings in Mathematics, Mechanics & Physics, Novosibirsk, 10-14 Sept 1990; Hydrodynamics Inst., 12 Sept 1990; Applied Physics Inst., 14 Sept 1990; High Temperatures Inst., 15 Sept 1990; Chemical Physics Inst., 17 Sept 1990; and Kurchatov Atomic Energy Inst., 18 Sept 1990.

Recent papers also illustrate that state-of-the-art diagnostics have been used in hypervelocity experiments. These include the standard diagnostics, such as high-speed cameras, radiography, interferometry, etc. In addition, unique methods have been developed, such as (1) mass spectrometry to characterize the degree of vaporization and the constituent products resulting from hypervelocity impact into geological materials; (2) light scattering experiments to characterize droplet size in debris clouds (Yakovlev et al., 1988); and (3) impact flash detectors to characterize dust particle impact at 80 km/s (Anisimov et al., 1987, 1988).

The experimental database developed with hypervelocity launching techniques has been used in practical applications. A key example is the use of Rusakov's data to design debris shields for Vega (Anisimov et al., 1984). In addition, there have been many other applications that refer to these extensive data, including numerical simulations of hypervelocity impact (Avrorin et al., 1990), proton beam damage (Leshkevich et al., 1989), laser beam irradiation (Akkerman et al., 1986; Burdonskiy et al., 1989), and railgun plasmas (Fortov, 1982).

A historical perspective of the experimental capabilities underpinning hypervelocity impact studies in the former Soviet Union is shown in Figure III.2.

In the following discussion, hypervelocity capabilities in the former Soviet Union are organized in the major technology areas. The principal hypervelocity technologies that have been discussed in published articles are described briefly first. These areas are defined below and discussed in Section III.C:

- Conventional Launchers
- Electromagnetic Launchers
- Particle Accelerators
- Particle Beams and Laser Techniques
- Special Hypervelocity Impact Experiments.

Following a discussion of the status of these capabilities, a comparison with US capabilities is presented. This perspective provides a view of the relative strengths and weaknesses of the Soviet program. Projections for future developments in hypervelocity technology in the successor states of the former Soviet Union are presented in Section III.D. Section III.E describes key research personnel in hypervelocity, the corresponding facilities, and the areas presently being emphasized in research and applications programs.

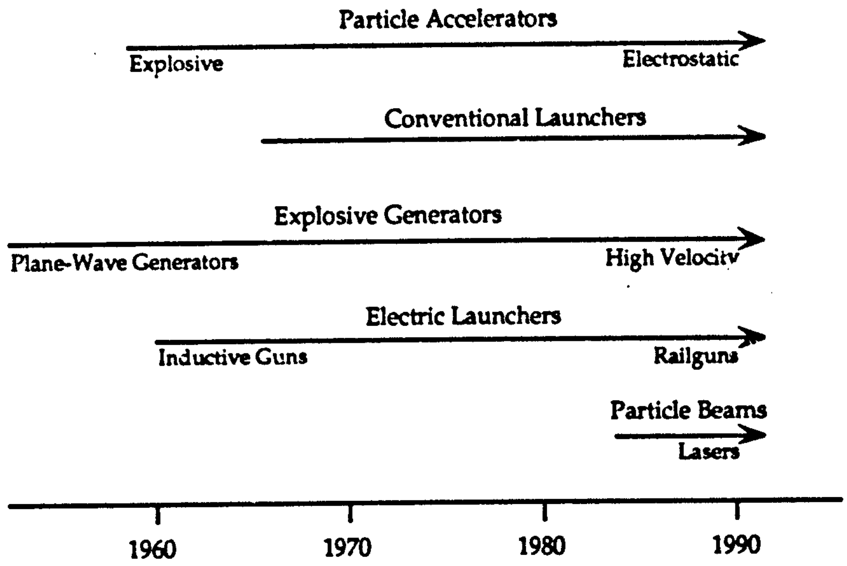

Figure III.2
Historical Development of Hypervelocity Capabilities in the Former Soviet Union

C. DISCUSSION

This section discusses the major Soviet hypervelocity technologies. The reader is referred to the references at the end of this chapter for more detailed information.

1. Conventional Launchers

The basic launcher techniques for dynamic impact studies have been developed at several Soviet institutions. These launcher capabilities cover the range from single-stage light gas guns, to propellant-driven guns and to two-stage light gas guns. These capabilities allow hypervelocity impact studies to velocities of about 11 km/s.

Light gas guns have been used for both ballistic impact experiments and for material property studies.[3]

The book by Zlatin and Mishin (1974) summarizes the status of ballistic ranges in the Soviet Union to 1974. This book provides a broad description of ballistic ranges and capabilities and, in addition, presents the details of several ranges outside the Soviet Union, particularly in the United States.

Soviet investigators have reported maximum velocities achieved with two-stage light gas guns of 11 km/s for projectiles weighing a fraction of a gram. This is comparable to recent results achieved with high-performance guns in Germany. Modified two-stage guns for launching gram-size projectiles to velocities greater than 12 km/s, as recently accomplished in the United States, have not been discussed in published reports.

Standard diagnostic techniques for ballistic ranges have been used in the major Soviet laboratories. These diagnostics have included the standard capabilities, consisting of stress gages, interferometric, optical and radiographic instrumentation, available in major laboratories outside the Soviet Union. In addition, other advanced diagnostics have been used. For example, Isakov et al. (1984) described a heated ballistic range for studying high-temperature plasma states of alkali metals to temperatures of 4300 K. This capability has been useful for increased understanding of plasma theories in programs at the Chemical Physics Institute. In another example, Yakovlev et al. (1988) described the adaptation of mass spectrometry to two-stage light gas guns for investigating the vapor debris resulting from the hypervelocity impact of geophysical materials.

A substantial body of ballistic data obtained with light gas guns has been generated by Merzhiyevskiy and coworkers at the Lavrent'yev Hydrodynamics Institute and by Mishin and coworkers at the Ioffe Physical Technical Institute. However, other facilities have also participated in these studies. A variety of impact studies have been performed, including (1) the dependence of penetration depth and crater size on velocity; (2) the effects of protective screens (Merzhiyevskiy and Titov, 1977);

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[3] James R. Asay, Private discussions with Gennady Mishin, Director of Research, A. F. Ioffe Physical Technical Inst., at the 18th Int'l. Symp. on Shock Waves, Sendai, Japan, 18 Jul 1991.

(3) the effects of oblique impact; (4) penetration in metals, porous, and brittle materials (Merzhiyevskiy and Titov, 1975); and (5) distribution of fragments from the impact. These studies are similar to those conducted in the United States and elsewhere.

Merzhiyevskiy and Titov (1987) gave a review of ballistic impact studies and discussed the wide range of topics conducted with light gas gun and other launcher techniques. Another recent book by Avrorin et al. (1990) has provided additional information regarding impact studies obtained with light gas guns.

A considerable number of the Soviet research publications have described hypervelocity impact studies in metals and geological materials. Most of these applications have referred to debris shield development, spacecraft protection, terrestrial planet studies, and equations of state. Military applications have not been discussed, although much of the work has had obvious military connections. For example, the investigations of Merzhiyevskiy and Fadeyenko (1973) concerning the destruction of liquid-filled tanks by hypervelocity impacts serve dual use in space and in military applications. Furthermore, the terminal ballistic studies by Andriankin (1966), Stepanov (1969), Kanel' and Pityulin (1984), Andilevko et al. (1986), Stepanov et al. (1986), Stepanov and Safarov (1986), and Kozhushko et al. (1987) have provided a strong basis for understanding impact mechanisms and designing better impact resistant materials.

In general, capabilities in conventional hypervelocity technologies, including launchers and diagnostics, in the former Soviet Union are comparable to capabilities in the United States and elsewhere. Trends for either increased or decreased use of light gas gun technology are apparent, although there is a steady output of published research using these techniques.

2. Electromagnetic Launchers

Interest in electric gun technology in the former Soviet Union dates back to the early 1960s. Bondaletov and Goncharenko (1971) described an inducting method for launching circular conductors to relatively high velocities. Velocities of more than 1 km/s have been obtained with 10- to 30-gram projectiles using this method. Later experiments by Bondaletov and Ivanov (1977) extended the velocity to 5 km/s.

These investigators also performed a few penetration experiments with the technique. Several other studies by Bondaletov and coworkers have expanded these studies to theoretical analyses and to different electrical configurations.[4] Velocities as high as 12 km/s have been obtained for aluminum cylinders of about 1.2-mm diameter with inductive launching techniques (Agarkov et al., 1974, 1981). A 1982 report by Golovin summarizes Soviet capabilities in electric guns and high-power batteries prior to 1982.[5]

The very early Soviet work (since 1965) in electromagnetic (EM) launchers was led by V. N. Bondaletov at the Istra Branch of the Electrotechnical All-Union Institute. The emphasis of this research was on induction methods, as indicated, with secondary interest in railguns. The induction launchers developed by Bondaletov included (1) a DC-gun in which the magnetic field moves rapidly toward the muzzle of the gun, thereby pulling the projectile along, and (2) an AC-gun that uses the interaction of a variable magnetic field and an induced field in the projectile. These two concepts are referred to in Western literature as "solenoid" guns (linear motor) and as "coil guns," respectively. Although considerable progress was made in this technology under Bondaletov's leadership, this technology has not found widespread application in penetration mechanics in recent years.

The Golovin report discusses the technical issues and the personalities of principal leaders in this area, which served to focus the early Soviet EM program on induction techniques versus railgun technology. An early railgun experiment performed by Sakharov (1965) used a magnetic flux compression method to accelerate 2-gram aluminum rings to velocities in excess of 100 km/s. However, Sakharov stated that the ring was totally vaporized at this velocity. No further experiments of this kind were reported by Sakharov's group.

Soviet development of railgun technology appears to have been minimal until the 1980s. Indeed, Golovin stated in 1982, "On the matter of EM guns, the Soviet developments are not on a par with US developments. . . ." This situation seems to

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[4] Bondaletov et al., 1983; Ber et al., 1984; Kalikhman, 1985; Kalikhman and Khorev, 1987; and Vlasova and Petrov, 1989.

[5] Michael N. Golovin, *A Survey of Soviet Research on Electric Guns and High-Power Batteries*, R-6133, Battelle Columbus Laboratories, Mar-Aug 1982.

have changed in more recent years, perhaps driven by railgun programs in the United States that were initiated in the late 1970s and early 1980s at Lawrence Livermore National Laboratory and Los Alamos National Laboratory. Presently, the program in railgun technology in the former Soviet Union is on a par with or perhaps slightly ahead of US capability.

Since the mid-1980s, the Soviet Union has sustained several major programs to develop hypervelocity railguns. These programs have been motivated by the need for a laboratory capability to launch gram-sized projectiles to velocities exceeding the capabilities of conventional launchers. Principal activities appear to be centered at the Lavrent'yev Hydrodynamics Institute (led by Gennadiy Shvetsov) and at the High Temperatures Institute (led by Ye. F. Lebedev). Both programs are staffed with 20 to 25 scientists and technicians.[6] Capacitors and explosive MHD generators are used at both facilities for power supplies. In addition, Lebedev uses a homopolar generator for some of his work. The railguns described at both laboratories employ small-bore barrels and plasma armatures. The facilities have been used primarily for basic studies of railgun physics.

Other hypervelocity railgun programs are located at the Ioffe Physical Technical Institute under the direction of Ye. M. Drobyshevskiy (1990), and the Kurchatov Atomic Energy Institute under V. F. Demichev.[7] Both of these have exploited the use of small-bore plasma-driven railguns. The Kurchatov gun has a stated goal to develop a deuterium pellet injector for Tokomak applications. This gun is currently in a very early stage of development, whereas the gun at the Ioffe Institute has been operating routinely at state-of-the-art performance (6 to 7 km/s).

The Soviet railgun development program has experienced the same limitations, particularly control of plasma armatures, as those in other programs. Velocities of about 6 km/s have been routinely achieved, although Drobyshevskiy (1990) recently reported velocities of 7.1 km/s with 1-gram projectiles, and Shvetsov (1990) has

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[6] Walter Herrmann, Trip Report.

James R. Asay, Trip Report on Travel to the III Lavrent'yev Readings in Mathematics, Mechanics & Physics, Novosibirsk, 10-14 Sept 1990; Hydrodynamics Inst., 12 Sept 1990; Applied Physics Inst., 14 Sept 1990; High Temperatures Inst., 15 Sept 1990; Chemical Physics Inst., 17 Sept 1990; and Kurchatov Atomic Energy Inst., 18 Sept 1990.

[7] James R. Asay, Private discussions with Gennady Mishin.

reported velocities up to 7.4 km/s.[8] The maximum performance of both guns is comparable to that achieved in other programs, notably in the United States (Japanese investigators have also recently reported railgun performance of 7.5 km/s).

The goals of the Soviet program appear to have been focused on understanding the physics of plasma armatures and the loss mechanisms that limit high-velocity performance. [9]The recent direction of their research is similar to that in other countries and includes investigation of materials, magnetic field configurations, plasma armature conduction mechanisms, loss mechanisms and dispersion of plasma armatures, interaction between railgun projectiles and barrels, etc.

For hypervelocity railguns under development in the former Soviet Union, the use of plasma armatures has been emphasized, but a theoretical study by Kalikhman (1985) indicated that solid armatures could be used to velocities up to 12 km/s. However, there is no documented evidence of this concept.

The maximum velocity capability of 7.1 km/s achieved at the Ioffe Physical Technical Institute is rather surprising, since railgun development prior to the Drobyshevskiy report (1990) was not identified at the institute. A possibility for this observation is that railgun technology was transferred from one of the other laboratories to the Ioffe Institute for use in a current application. This is supported by the fact that research conducted at the Ioffe Institute has had a definite orientation toward ballistics and material property studies. Although many applications of interest would not benefit directly from the current velocity capabilities of railguns, the experience gained in developing ballistic diagnostics for use on railguns would be invaluable as the performance continues to improve and the capability becomes routine for studies at velocities exceeding those of conventional launchers.

There are several differences between railgun programs in the former Soviet Union and the United States. One of these relates to railgun preparation methods. Shvetsov's group has been exploring the use of explosive compaction techniques for rapid and inexpensive fabrication of railgun barrels and has successfully prepared

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[8] James R. Asay, Trip Report.

[9] Shvetsov et al., 1986, 1987a-b; Kondratenko et al, 1986, 1988; Stadnichenko and Shvetsov, 1988; Stadnichenko et al., 1986; Anisimov et al., 1989)

barrels in this manner.[10] The stated purpose has been for inexpensive preparation of railgun barrels for one-time use; the barrels have been disassembled after one shot so barrel damage and erosion could be examined. However, the technique would be extremely valuable for fabricating barrels for use in military applications. Furthermore, Soviet researchers have been gaining valuable experience in fabricating inexpensive barrels with non-traditional methods. This method is unique and, apparently, has not been pursued in other programs.

Another difference between programs in the former Soviet Union and the United States is that Soviet researchers have not reported the development of large-bore (for example, 50-mm bore diameters) "demonstrator" hypervelocity railguns, similar to the Thunderbolt program in the United States. The development of such facilities would imply a definite military orientation, particularly for SDI applications.

Soviet scientists extremely knowledgeable in plasma physics, including V. Ye. Fortov, have recently been involved in these programs, particularly at the High Temperatures Institute (Kondratenko et al., 1986, 1988). With a focus on the basic physics issues and the comparatively large effort, the chances are good that researchers in the successor states of the former Soviet Union will achieve major progress, and perhaps a breakthrough, in hypervelocity railguns.

Electronic launch techniques encompass a variety of techniques and include both railguns and induction launchers, which are being intensively studied in several current research programs. Recent mention of induction launchers was made in papers by Baltakhanov and Ivanov (1982) and by Vlasova and Petrov (1989), which gave a theoretical analysis of both the inductive heating of aluminum conductors and the resulting velocity that could be achieved before onset of melting. These calculations indicated that velocities as high as 16 km/s could be attained with inductive launchers. However, there is no documented evidence for the operation of inductive launchers in the former Soviet Union at these velocities.

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[10] Walter Herrmann, Trip Report.
James R. Asay, Trip Report.

3. Explosive Launcher Capabilities

Soviet laboratories have pursued programs to develop explosive techniques for launching thin plates to very high velocities. This technology provides a basic method for determining the high-pressure equations of state of materials. Equation-of-state studies performed by Al'tshuler and others illustrated the fundamental properties that can be obtained with these methods.[11]

The basic explosive shock wave experiment for equation-of-state studies consists of using a plane wave explosive lens for planar loading of specimens (Avrorin et al., 1990). This is a standard technique and Soviet capabilities in this area have been equivalent to those elsewhere. However, Soviet scientists have developed advanced explosive plate-launching techniques that exceed, by far, the mass-velocity plate launch capabilities at other facilities outside the former Soviet Union.

The basic technique used at the Chemical Physics Institute to achieve extremely high velocities consists of a multi-stage explosive device that launches metallic disks (less than a millimeter thick) to velocities of 13 km/s (Avrorin et al., 1990). This technique has been used to produce high-pressure equation-of-state studies in the laboratory and has been used to study metallic vapors and plasmas (Avrorin et al., 1990; Bushman et al., 1984; Bushman et al., 1986). It has been used primarily in the former Soviet Union, although French investigators have also reported use of the method.

Soviet investigators have routinely used this technique to generate a large body of data on the dynamic response of materials, principally metals, to shock loading. It has been noted in visits to the Chemical Physics Institute[12] that modern diagnostics have been used with these techniques to acquire experimental data. Diagnostics include modern electronic image converter cameras, velocity interferometer system for any reflector (VISAR) and optical recording velocity interferometer system (ORVIS), pyrometry, stress gages, and radiography. The data have been used to vali-

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[11] See, for example, Fortov et al., 1974; Al'tshuler et al., 1980; Avrorin et al., 1980; Fortov and Yakubov, 1984; Glushak et al., 1989.

[12] Walter Herrmann, Trip Report.
James R. Asay, Trip Report.

date theoretical models of the equation of state,[8] primarily for expanded state response, that is, vapors and plasmas.

A more recent variation of this method, illustrated in Figure III.3, uses a conical explosive generator to launch thin flyer plates to velocities of 16 km/s. Data have been obtained with this device, referred to as the "explosive Mach shock wave generator," in copper to 14.1 Mbar (Avrorin et al., 1990). This is a record velocity and pressure for laboratory-scale equation-of-state experiments. Two-dimensional computer simulations were used to optimize the geometry of this device (Avrorin et al., 1990).[13]

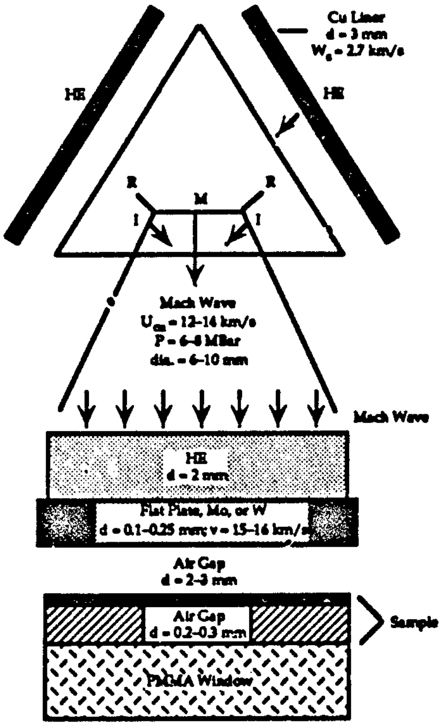

Figure III.3
Schematic of Conical Explosive Generator Used to Launch High-Velocity Plates for Equation-of-State Studies

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[13] Walter Herrmann, Trip Report.

The use of these generators for equation-of-state work has been centered primarily at the Chemical Physics Institute. Kirko et al. (1987) indicated that jetting techniques have been used to obtain equation-of-state data in organic materials to 100 GPa with 10- to 30-km/s jets. The details of the technique and data were not presented for critical evaluation, but this would represent record capability, if true.

The explosive generators developed by Soviet laboratories have resulted in a unique capability for studying the equations of state of vapors and plasmas, and therefore have provided an advantage in characterizing materials in thermodynamic regimes important to hypervelocity impact. In particular, the increasing Soviet use of numerical techniques for analyzing impact events, coupled with experimental methods for characterizing important materials to hypervelocity impact, provides an important capability for predicting hydrodynamic effects in several applications.

In addition to launching particles with jetting techniques, explosively launched jets were used for several years in the Soviet Union to study penetration effects; there are several published papers on this subject.[14] Merzhiyevskiy and Resnyanskiy (1987) have used a finite-element numerical code to design a conical housing to produce a jetting condition referred to as "reverse cumulation," which forms a relatively compact body from the shell of the shaped charge. This technique could be used to simulate high-velocity particles for hypervelocity testing. The calculations were confirmed experimentally with velocities on the order of 4 km/s, but applications of the method were not reported. Other jet methods have involved the acceleration of small particles (0.1 to 1 mm in diameter) by using aerodynamic forces to accelerate particles in a gas or plasma flow. Sil'vestrov (1979) described a variation of explosive methods for accelerating particles to high velocities. This technique has been used by Urushin et al. (1977) to simulate the impact of stony meteorites to velocities of 8 km/s.

Although there appears to have been a capability for using jetting methods to simulate hypervelocity particles, this does not appear to currently be a large activity in the former Soviet Union. Also, the development of jetting methods to launch gram-sized particles to velocities greater than 11 km/s has not been published.

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[14] For example, see Merzhiyevskiy and Resnyanskiy, 1987; Kovtun and Mazanko, 1988; Titov, 1979; Merzhiyevskiy et al., 1986; Merzhiyevskiy and Titov, 1987.

These techniques are now being used in the United States and Germany for launching particles to 12 km/s.

The explosive techniques developed by Fortov and coworkers for equation-of-state experiments would be equally useful for hypervelocity ballistic experiments. However, there was no evidence for the use of these techniques in ballistic experiments, such as the design of debris shields for low-Earth orbit applications (gram-sized projectiles with velocities of 10 to 14 km/s are necessary in these studies). The capability would also be useful for studying advanced hypervelocity lethality and vulnerability concepts, although these studies were not reported. An alternate approach would be to use computer simulations for specific applications, using the equation-of-state experiments for validation of the computer capabilities. The Soviet laboratories reviewed in this assessment certainly have had the capability for performing these analyses.

Computer simulations have been used at the High Temperatures Institute both to design and to analyze hypervelocity impact events. It is important to note that the extensive database generated with explosive generators is being actively used for validating computer models of material response (Avrorin et al., 1990, give a good review of current capabilities). Some evidence was also noted for the development of computational capabilities for analyzing coupled hydrodynamic-structural response.

A definite trend at several major laboratories in the former Soviet Union has been to place more reliance on computing for evaluating hypervelocity impact phenomena, particularly under the leadership of V. Ye. Fortov. It is noteworthy that Fortov is a co-author on most of the substantive papers involving numerical simulations of hypervelocity impact events. Several recent examples that illustrate these capabilities include the work by Leshkevich et al. (1989), Anisimov et al. (1988), and Avrorin et al. (1990).

As computing becomes more prevalent in the successor states of the former Soviet Union, the high-velocity experimental capabilities will have increasing value for validating equations of state used in computer simulations. A full-system capability for predicting hypervelocity effects would provide commercial and military advantage for quickly evaluating new concepts and for performing cost-benefit trade-off studies.

4. Particle Accelerators

A large variety of techniques have been developed in the former Soviet Union for accelerating small particles to hypervelocities. These have included (1) plasma drag accelerators for launching microgram particles to velocities over 15 km/s, (2) gas acceleration in jets, (3) liquid hydrogen techniques, and (4) electric acceleration. Many of these techniques date back to the early 1960s. Sil'vestrov (1975) provided an assessment of several of these methods.

One of the major accomplishments in particle accelerators for hypervelocity impact studies was made by Rusakov and coworkers, who developed capabilities for launching small particles to hypervelocities in the mid-1960s and have used this technique for a large number of hypervelocity impact studies.[15] The experimental method involved launching a column of particles (typically tungsten) contained initially in a column of paraffin to velocities of 20 to 30 km/s. The actual technique has not been completely described by Rusakov, but apparently uses the electrical explosion of a dielectric as in an electric gun. A variety of other techniques could be used, such as gas or plasma drag.

For example, a method developed by Voytenko (1965) for producing high-velocity gas jets could easily be used in these applications. This method used explosives to accelerate gas in a hemispherical cavity (Voytenko, 1965, 1966; Voytenko and Kirko, 1978). Gas velocities as high as 90 km/s have been achieved with hydrogen driving gas. Voytenko and Kirko (1978) also discussed a novel technique for accelerating particles for chemical synthesis and have applied the technique to the synthesis of metallic carbides, borides, nitrides, and silicides. The method could be easily used for accelerating particles for hypervelocity impact applications, as described by Rusakov.

Rusakov's method of launching particles has been used to examine a range of impact-related phenomena, including the penetration depth of hypervelocity particles, the effect of velocity on crater dimensions, the enhancement of momentum

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[15] For example, see Rusakov, 1966, and subsequent papers.

delivered to targets in high-velocity impacts, and the effects of vaporization and recondensation (Rusakov, 1966, 1969, 1975; Rusakov et al., 1968, 1977, 1979, 1987).

Rusakov has continued to use this technology for several years. Recently, he reported data obtained with the method to develop dust shields for the Vega space probe (Rusakov and Lebedev, 1987). However, the technique has not been used to a large extent in recent research programs. There have also been no obvious attempts to extend its capability in either velocity or particle mass.

Variation of the technique could, in principle, be used to launch intact plates to velocities of about 30 km/s. However, the method produces extremely high gas pressure (on the order of 1 Mbar) on plates of appreciable mass for velocities exceeding 10 km/s. US research has shown that plate breakup is a major problem under these loading conditions.

Hypervelocity studies conducted with this method have provided Soviet researchers with a database for testing cratering theories at velocities higher than achievable with most other techniques. The technique has not been reported outside the former Soviet Union, but other methods, such as plasma drag accelerators and van de Graff accelerators, are being used in the West to achieve comparable velocities. From this standpoint, this technology does not offer a unique advantage for hypervelocity impact testing. However, the early database generated by Rusakov and associates surpasses that available elsewhere and is invaluable for providing insight into hypervelocity phenomena and in guiding practical applications.

Electrostatic accelerators have also been used by Soviet investigators to study impact effects at velocities in the tens of kilometers-per-second range. For example, recent research by Abramov et al. (1991) and Semenov (1991) has been directed toward the study of the effects of dust particle impact at velocities of 40 km/s. This capability is comparable to that available with van de Graff particle accelerators developed in the United States and Europe.

5. Particle Beams and Laser Techniques

Lasers and particle beam accelerators have been used by Soviet investigators to support major hypervelocity impact programs. Burdonskiy et al. (1989) have used high-intensity lasers to accelerate 6-μm foils to velocities of about 60 km/s. Akkerman et al. (1986) have used relativistic electron beams to study high-pressure material behavior, while Leshkevich et al. (1989) have employed proton beams to study particle beam interactions with targets.

A novel application of high-power lasers for supporting hypervelocity research involved their use as a design tool for debris shields used for the Vega space probe (Anisimov et al., 1984, 1985, 1986a-b, 1987, 1991). Information on the particle distribution in the tail of Halley's comet indicated that dust particles with velocities on the order of 80 km/s would impact the spacecraft. Anisimov et al. (1985) used laser deposition to estimate the fragment velocities and mass that dust particles of 10^{-7} grams would create by impacting debris shield configurations at 80 km/s. Debris patterns and the resulting damage to structures produced by laser deposition were used in conjunction with hydrocode analyses to design successful stand-off shields for the space probe (Anisimov et al., 1986).

Recent Soviet investigations into the use of high-power lasers and particle beam research have continued at a modest level; recent applications appear to have been focused on equation-of-state studies. Published research was not noted on the use of these methods for producing target damage or in mitigating damage to systems from particle beam or laser irradiation; such emphasis would indicate military application. However, Soviet laboratories clearly have had the capabilities for studying these effects. A limited amount of research has been done in Western laboratories with electron beams and lasers for equation-of-state and flyer plate applications, but they are not standard laboratory tools.

6. Special Hypervelocity Impact Experiments

Soviet investigators performed an experiment onboard the Vega space probe that illustrated their approach to solving hypervelocity impact problems. Investigators from several institutions were involved in this program and several experimental and computational capabilities were combined to solve the complex problems associated with this experiment. Analyses leading up to this experiment and analysis of the results were summarized in a series of papers by Anisimov et al. (1984, 1985, 1986, 1987, 1991), Agureykin et al. (1984), Akkerman et al. (1986), and Leshkevich et al. (1989).

One of the principal goals of the Vega mission was to investigate the dust envelope of Halley's comet, that is, an analysis of the chemical and isotopic composition of the particles, physical properties of the dust, the size distribution of particles, and the spatial density of particles in the cloud. Engagement velocities of dust particles were estimated to be on the order of 80 km/s. At these velocities, serious damage could result to the spacecraft, which necessitated the use of protective debris shields. The extensive database developed by Rusakov and colleagues provided useful guidance for the initial design of the shields. However, it was found necessary to implement new experimental diagnostics, as well as the use of computational analysis, for the final design.

At least two years prior to the expected engagement (March 1986),[16] an intensive effort was initiated at several institutes. V. Ye. Fortov appeared to be directing this program, since his name appears in essentially all of the related publications. Early in the program, Soviet scientists noted that successful design of the shield would require extensive two-dimensional computer simulations to characterize impact damage and to design instrumentation for diagnosing hypervelocity impacts. A pivotal paper by Agureykin and colleagues (1984) stated that

> . . . since direct quantitative experiments in the speed range near 100 km/s are impossible at present, the only way to obtain more accurate information on high-speed disintegration is numerical computation.

This requirement seems to have established collaborative efforts between the group at the Chemical Physics and High Temperatures Institutes, under the leadership of Fortov and the scientists B. P. Kryukov and V. F. Minin who were developing parallel computing capabilities at the time (believed to be at the Applied Physics Institute, Novosibirsk, their current affiliation). A major collaboration appears to

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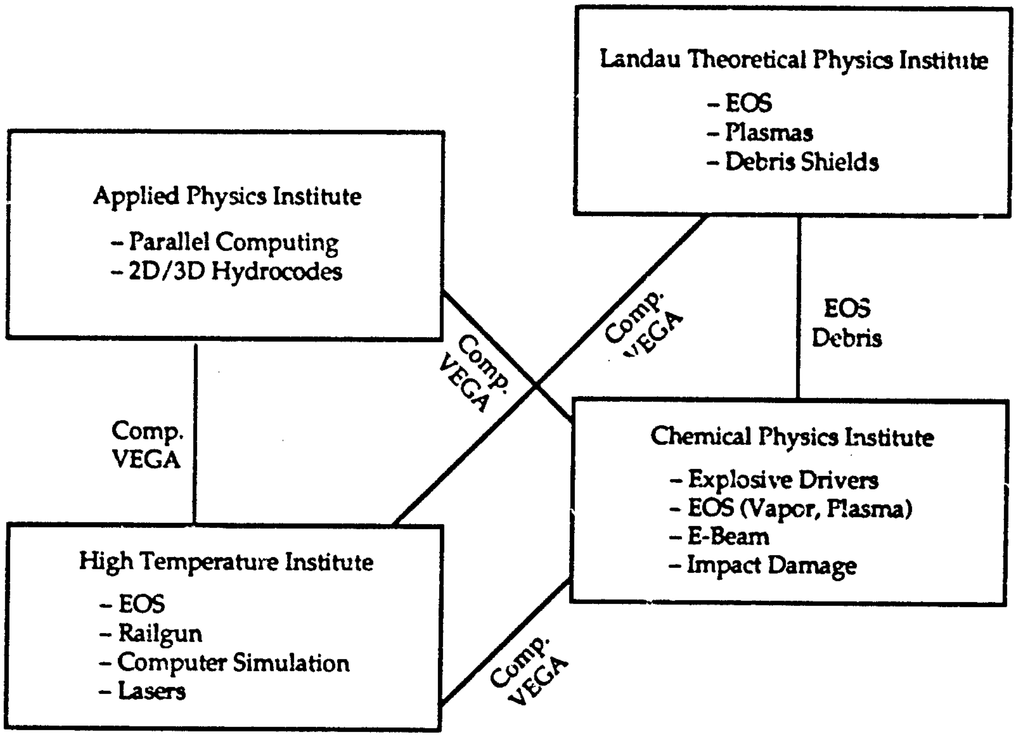
[16] The 1984 article by Agureykin et al. includes extensive technical investigations that would have had to be initiated one to two years prior to publication.

have been established for the purpose of designing and implementing this experiment. Figure III.4 summarizes the different institutions involved.



Preparation and implementation of the Vega space probe appeared to be the driving force behind the collaborations.

Figure III.4
Collaborations Noted Between Major Institutes

Agureykin's paper illustrates the use of two-dimensional computer codes for analyzing 80 km/s dust particle impacts on the spacecraft's debris shields. The computations relied heavily on the extensive high-pressure material properties database generated by Al'tshuler and coworkers and the expanded equation of state for vaporization developed by Bushman and coworkers (see, for example, Bushman et al., 1990). Realistic mechanical models for material strength, yield behavior, and spallation strength for aluminum were also incorporated in the computer codes. Hypervelocity particle impact was experimentally simulated through laser techniques, as mentioned above, with deposition energies equivalent to the initial kinetic energy of the expected particles. Numerical calculations of the laser experiments were in agreement with experimental results and provided validation for numerical design of the shield configuration.

This combination of experiment and calculation led to the design of a dual shield of aluminum and composite/aluminum that was successfully fielded. In addition, diagnostics onboard the probe successfully recorded impact of a dust particle at 80 km/s and transmitted this information to Earth. The penetration results obtained in this experiment are unique and have been referred to in several subsequent publications (see, for example, Avrorin et al., 1990; Anisimov et al., 1991).

The ability to carry out a complex hypervelocity experiment of this magnitude is indicative of the breadth of capabilities in the former Soviet Union in hypervelocity impact phenomenology. The timely success of this project suggests that other major programs in the successor states involving hypervelocity phenomenology could be equally successful if the right combination of researchers were to be involved. Several scientists were instrumental to this program, but Vladimir Fortov appears to provide the technical leadership necessary to integrate the various activities.

7. Emphasis of Soviet Applications in Hypervelocity Impact Phenomenology

One of the original motivations of Soviet interest in hypervelocity impact has been to study the effects produced on space structures. This interest dates back to the early work of Stanyukovich (1961), Nazarova (1961a-b, 1972), and Lavrent'yev (1961). This concern has continued to the present, as illustrated by the extensive work of Anisimov, Fortov, Bushman, Al'tshuler, and others. The bulk of this work has concerned meteorite impacts on space structures, as opposed to impacts with orbital debris, which results in different mass and velocity ranges and different configurations for debris shields. Discussions related to the development of protective measures for orbital debris impact were not noted in the published literature although the experimental methods that have been developed, particularly, the explosive generators, could be used for these studies. In this regard, Soviet investigators have been active in promoting commercial use of the experimental and numerical capabilities for designing advanced debris shields.[17]

A major motivation for the equation-of-state studies with hypervelocity launchers has involved the study of plasma and vaporization physics (Lomadze, 1987; Fortov et al., 1974, 1976, 1984). There are several current applications that would benefit from a better understanding of plasma physics, notably Tokomak operation, hypervelocity railgun armatures, astrophysics, and rocket technology (particularly for nuclear propulsion). The extensive Soviet work in this area has provided the successor states with technical insight and the ability to address difficult applications problems.

It is noteworthy that the published literature has made no mention of weapons-related hypervelocity applications, such as studies related to hypervelocity lethality, vulnerability or studies of space armor materials. An example would include the ballistic curves developed by investigators in other laboratories. There has also been no mention of weaponizing the techniques that have been discussed. An example would include mass-velocity requirements for a demonstrator electromagnetic launcher for re-entry vehicle interception.

8. Comparison with US Capabilities

The relative strengths and weaknesses of the Soviet program in hypervelocity technology compared to similar capabilities at other laboratories are summarized below.

a. Conventional Launchers

- Soviet capabilities have been similar to those in the United States for both equation-of-state work and ballistics experiments. However, it is noteworthy that large-bore (~100-mm bore diameters) have not been discussed in the Soviet literature. Larger-bore light gas guns are useful in evaluating military application, such as system response to hypervelocity impact,

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[17] Walter Herrmann, Trip Report.
James R. Asay, Trip Report.

whereas the smaller-bore guns are useful in equation-of-state and phenomenology studies.

- Instrumentation diagnostics used in Soviet experiments have been equivalent to US capabilities. Soviet laboratories have used a combination of imported equipment and equipment made in that country.

- Soviet research activity involving conventional launchers, including two-stage gas guns, has remained steady. Reported activity has been similar to that in the United States.

- The focus of Soviet research has been on metals and geophysical materials. The extent of ballistic penetration experiments on geological materials has been greater than that in the United States. Some research on ceramics materials that could be used in military application has been reported.

- Overall, Soviet technology has been comparable to US capabilities; major weaknesses in this program are not apparent.

b. Electromagnetic Launchers

- Recent Soviet research efforts in hypervelocity railguns have been centered at two institutions, with modest activity at two others. The level of effort (about 50 investigators) in railgun research and development for hypervelocity applications (10 km/s) has been similar, or somewhat larger, than that in the United States. *The status of research in the former Soviet Union is judged to be on a par with that in the United States.*

- The reported velocity capability of the Soviet hypervelocity railgun program has been comparable to that achieved in the United States, or be slightly advanced. Two institutions have recently reported railgun velocities exceeding 7 km/s (velocities higher than this were reported in US laboratories in the mid-1980s, but the results have not been repeated except for high-velocity injection into railguns). Major Soviet breakthroughs leading to higher velocities have not been reported.

- The recent emphasis of Soviet research on hypervelocity railguns has been focused on understanding physical processes that limit high-velocity performance. These studies have recently been performed on prototype small-scale guns. The Soviet ability to focus on the fundamental mechanics of operation over a long period is judged to be a strength.

- There has been a broader supporting technical base for railgun research at Soviet universities and other facilities outside the main institutes involved in railgun activity. This approach and level of effort are similar to those in the United States.

- Soviet research activities have been focused at institutes involved with nuclear weapons research and have involved scientists with plasma physics and hydrodynamics background. However, numerical investigations with two- or three-dimensional MHD computer codes to investigate the physics of railgun operation was not noted. The lack of this capability may be a weakness of their program. MHD studies of plasma armature physics have been more prevalent in US programs.

- Soviet experimental and theoretical research on induction launchers has been reported, beginning in the 1960s. Use of induction guns for penetration experiments appears to have been limited since the mid-1980s.

- Soviet research on "demonstrator railguns," that is, large-bore guns that could be used in military applications was not identified. The lack of this activity could be viewed as a weakness, compared to US programs.

c. Explosive-Driven Launchers

- Soviet researchers have developed explosively driven flyer plate technology for equation-of-state studies of high-pressure equations of state and studies of vapors and plasmas. These investigations have been conducted routinely in the laboratory for plate velocities to 13 km/s. *This is a definite advantage over US capability.*

- Two-dimensional computer simulations have been used by Soviet researchers for about the past five years to optimize the "Mach shock wave generator," which uses a conical configuration to achieve 16 km/s. This technique has also been used for equation-of-state studies. A strength of the Soviet program has been the close collaboration between researchers at the Applied Physics Institute, Novosibirsk, which has the expertise in two- and three-dimensional hydrocodes necessary for these calculations, and researchers at the Chemical Physics Institute, Chernogolovka, who apply these capabilities in equation-of-state experiments.

- Soviet experimental capabilities have been applied primarily to equation-of-state studies of shock-induced metal vapors and plasmas and the techniques have generated, by far, *the largest database of expanded equation-of-state response compared to other laboratories world wide. This is judged to be a major strength for validating equation-of-state and computer capabilities.*

- Research was not reported in which the explosively driven flyer plate techniques were used for ballistic impact experiments.

d. Particle Accelerators

- Techniques were developed in the 1960s, using explosive and electric methods, for accelerating a cloud of metal particles (typically tungsten) to velocities of 25 to 30 km/s. Soviet capabilities for launching high-density particles to 30 km/s have been comparable to those available in other laboratories, although this particular technique is not being used elsewhere.

- The hypervelocity impact studies conducted with this technique produced a large Soviet database of impact phenomena that has not been equaled elsewhere. Effects of vaporization, condensation, and electrical effects in debris clouds have been studied. *This has resulted in unique expertise in hypervelocity phenomena, which has been a strength of their program.*

- Electrostatic accelerators have also been developed in the former Soviet Union for accelerating microscopic particles to very high velocities (greater than 30 km/s). This capability is similar to that available in the United States and elsewhere.

- A weakness of all current particle accelerator methods, including those in the former Soviet Union, is the uncertainty of particle conditions prior to impact, which may prevent accurate validation of numerical or analytical techniques.

e. Particle Beams and Laser Techniques

- A modest Soviet level of effort has been reported for the use of particle beams and lasers to simulate impact damage and to accelerate thin flyers to hypervelocities. Recent Soviet activity in this area has been greater than that in the United States for impact-related studies.

- *A strength of the Soviet hypervelocity program has been the ability to use a broad range of techniques, such as laser deposition, for experimental simulation of hypervelocity impact damage.* Correlation between laser energy deposition and kinetic energy deposition has been done via computer analysis. Similar approaches are employed in the United States.

- The use of particle beams or laser techniques for lethality studies was not reported.

f. Special Hypervelocity Experiments

- Soviet investigators accomplished a major technical feat by performing a hypervelocity impact experiment involving dust particle impact on the Vega space probe at 80 km/s. *This work is unparalleled in other programs, although the technology base exists at several laboratories for performing these experiments.*

- A strength of the Soviet capability for performing such complex experiments has been embodied in the extensive collaborations between institutions and scientists necessary to accomplish this experiment.

g. "Resounding Silences" (that is, no published research literature found)

- No railgun "demonstrator" for weapon applications.
- No use of hypervelocity techniques for lethality or vulnerability studies on weapon materials or systems.
- No use of particle beams or lasers in experiments that would simulate lethality or vulnerability applications.

h. Cross-Cutting Technologies

These are technologies that have application across different technical areas. Activity has been noted in these different areas related to hypervelocity impact research. Future surveys of these areas should include assessment of applications to hypervelocity research.

- Use of computational simulations can substantially expand hypervelocity impact studies by allowing analysis of conditions not achievable experimentally.
- Massively parallel computing can expand the analysis of hypervelocity impact experiments and the design of improved explosively driven launchers by allowing the solution of larger problems.
- Use of particle beams and lasers has been used to simulate hypervelocity impact phenomena.
- "Superdeep penetration" has been studied for penetration enhancement at lower velocities (Al'tshuler et al., 1989; Andilevko et al., 1990).

The differences in approach between Soviet and Western programs in hypervelocity impact and the relative comparisons of Soviet and US capabilities are summarized in Tables III.1 and III.2.

Table III.1
DIFFERENCES IN APPROACH BETWEEN PROGRAMS IN THE FORMER SOVIET UNION AND THE UNITED STATES IN HYPERVELOCITY IMPACT RESEARCH

Former Soviet Union	United States
• Simple diagnostics	• Sophisticated diagnostics
• Large, broad database	• Small, focused database
• Focus on extending the technology to higher velocities	• Extensive use of existing experimental technology
• Relatively short published description of technique	• Relatively extensive published description of experimental technique
• Reliance on analytic expressions (but changing emphasis)	• Large reliance on theory and computer simulation for extrapolation
• Research publication is often delayed a few years	• Research is published early

Table III.2
RELATIVE COMPARISONS BETWEEN THE FORMER SOVIET UNION AND THE UNITED STATES IN HYPERVELOCITY IMPACT RESEARCH CAPABILITIES

minus sign = equivalent capabilities, plus = advantage
plus in parenthesis = a slight advantage, double plus = a significant advantage

Enabling Capability	Former Soviet Union	United States
High Velocity (> 5 km/s launchers)		
Conventional guns	–	–
Particle accelerators	+	
Railguns	(+)	
Explosive launchers	++	
Particle beams/lasers	(+)	
Special experiments (Vega)	+	
Experimental Database		
Vapor and plasma equation of state	+	
Ballistic phenomena (< 10 km/s)	–	–
Very-high-velocity phenomena (> 10 km/s)	+	
Analysis Capability		
Equation-of-state/material properties		+
Fragmentation/debris theories		+
Analytic relations for penetration	(+)	
Computing and numerical simulation		+

D. PROJECTIONS FOR THE FUTURE

Research in the former Soviet Union in several areas of hypervelocity impact technology has been continuing at a reasonable level of effort and in a systematic fashion. The trends and projections for capabilities in the successor states in hypervelocity technology are summarized as follows:

- *The ongoing major commitment at former Soviet laboratories to understanding the physics of railgun operation with small-bore guns at high velocities could lead to a breakthrough in this technology.* Evidence of the development of larger-bore guns would be significant and could indicate that current performance problems have been resolved. Discussion of the use of railguns, or other electromagnetic launchers, for Earth-to-orbit launch would also be significant and potentially have a military application.

- As a consequence of their continuing work in explosively compacted railgun barrels, investigators at the Lavrent'yev Hydrodynamics Institute in Novosibirsk may be successful in developing routine techniques for the rapid and inexpensive preparation of railgun barrels; *this would have military significance.* Developments of this technology should be followed.

- A resurgence of research in the development of induction launchers (coil guns) in the Soviet successor states would signify a broader application base for electromagnetic launchers and indicate possible military use.

- *There appears to be increased emphasis on using computer simulation in hypervelocity impact simulations.* The very large database that Soviet investigators have developed for expanded material response would provide researchers in the successor states an advantage in validating computer simulations. This would enable use of computer simulation for realistic predictions of impact damage, as well as in the analysis and design of advanced experimental techniques.

- There is continuing interest in the response of structures to hypervelocity impact. Advanced capability would constitute coupled hydrodynamic-structural computer codes for evaluating complex systems. *Evidence for* *coupling hydrocodes with structural codes and any evidence for experimental validation of this capability in the hypervelocity regime would be significant.*

- *The ongoing research in particle beam and laser deposition could result in new weapon concepts. Published information on the effects of debris resulting from these experiments on any kind of target would be significant.*

- There is an increasing interest in determining the fragmentation patterns obtained from high-velocity impact (see, Inogamov et al., 1991) and the interaction of debris with structures. This could lead to much better capabilities for predicting lethality or vulnerability effects in weapon applications.

- V. Ye. Fortov appears to provide technical leadership for integrating diverse technical activities at several institutions and for incorporating state-of-the-art experimental and theoretical capabilities into the applications. *Fortov's connection to other programs, for example, development of advanced ceramics, would be significant.*

- The concept of "superdeep penetration," which has been studied at relatively low velocities, is being extensively studied at lower velocities. Similar studies at hypervelocities would be significant and possibly indicate a breakthrough for military applications.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Soviet scientists engaged in hypervelocity programs have often been involved with other major activities, such as nuclear weapons research. Extensive collaborations have often been established between scientists at different facilities, and the author affiliation is usually given as a single institution. In many cases, the authors are known to be affiliated with other institutions. Vladimir Fortov is a particular example. He has indicated in private conversations and through publications that he has a joint appointment as Director of Physical Hydrodynamics at the Chemical Physics Institute in Chernogolovka, and at the High Temperatures Institute in Moscow. He is also affiliated with other institutes in papers published jointly with other colleagues. In Table III.3, all researchers who have been affiliated with an institution in a reported publication have been listed under that institution.

Often, a clear distinction of a particular scientist's contributions in the hypervelocity area is not known. For this reason, Table III.3 identifies individuals who have been associated with activities directly or indirectly related to hypervelocity research, even if that is not their principal focus. Table III.4 lists key individuals and specialties related to hypervelocity research capabilities.

Table III.3
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— HYPERVELOCITY IMPACT CAPABILITIES

Applied Mathematics & Mechanics Institute,
Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)

I. Ye. Khorev
A. V. Radchenko
A. I. Korneyev
V. A. Gorel'skiy
V. F. Tolkachev
A. N. Bogomolov
N. T. Yugov
V. A. Gridneva

Applied Physics Institute, Novosibirsk (Russia)

Vladilen F. Minin (Director)
Boris P. Kryukov

Atomic Energy Institute im. I V. Kurchatov, Moscow, Troitsk (Russia)

V. F. Demichev
I. V. Kurchatov
V. V. Makarov
L. B. Nikandrov
V. P. Smirnov

Belarussian State University im. V. I. Lenin, Minsk (Belarus)

L. V. Al'tshuler
S. K. Andilevko
S. M. Usherenko
G. S. Romanov

Chemical Physics Institute,
USSR/Russian Academy of Sciences, Chernogolovka (Russia)

V. Ye. Fortov
V. A. Agureykin
V. A. Gorel'skiy
V. K. Gryaznov
M. V. Zhernokletov
A. M. Prokhorov
K. I. Kozorezov
S. I. Anisimov
G. I. Kanel'
V. F. Tolkachev
A. V. Bushman
I. K. Krasyuk
V. Ya. Ternovoy
L. I. Mirkin
A. P. Zharkov
A. N. Dremin
I. Ye. Khorev
A. I. Leont'yev
B. L. Glushak
P. P. Pashinin
A. S. Filimonov
S. S. Girgoryan

Table III.3
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—HYPERVELOCITY IMPACT CAPABILITIES (cont'd.)

Computational Center, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)

N. N. Yanenko
V. M. Fomin
K. A. Kroshko
V. P. Shapeyev
V. V. Liseykin
Yu. A. Shitov

Earth Physics Institute im. O. Yu. Shmidt, USSR/Russian Academy of Sciences, Moscow (Russia)

I. V. Nemchinov

Electrotechnical All-Union Institute, Istra (Moscow Region—Russia)

V. N. Bondaletov
T. G. Vlasova
S. R Petrov

High Temperatures Institute, USSR/Russian Academy of Sciences, Moscow (Russia)

V. Ye. Fortov
S. I. Kuz
M. I. Bespalov
Gennadiy I. Kanel'
Andrey Z. Zhuk
M. E. Kulish
Ye. F. Lebedev

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)

S. K. Godunov
L. A. Merzhiyevskiy
Yu. I. Fadeyenko
Yu. L. Bashkatov
A. D. Matrosov
A. A. Deribas
A. D. Resnyanskiy
G. A. Shvetsov
I. A. Stadnichenko
V. I. Mali
V. M. Titov
A. G. Anisimov
V. P. Chistyakov
N. A. Popov

Mechanics Institute Scientific Research Institute, Moscow State University im. M. V. Lomonosov, Moscow (Russia)

L. A. Chudov
A. Ya. Sagomonyan

Minsk (Belarus—facility not identified)

R. V. Arutyunyan
L. A. Bolshov
M. F. Kanevskiy

Moscow State Technical University im. N. Ye. Bauman, Moscow (Russia)

G. P. Men'shikov
V. A. Odintsov
V. P. Muzychenko
L. A. Chudov
E. I.Andriankin
K. P. Stanyukovich

Table III.3
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—HYPERVELOCITY IMPACT CAPABILITIES (cont'd.)

Moscow State University im. M. V. Lomonosov, Moscow (Russia)

V. I. Kondaurov
K. I. Kozorezov
I. B. Petrov
L. I. Mirkin
A. S. Kholodov
S. S. Girgoryan

Optical Physical Measurements All-Union Scientific Research Institute, USSR/Russian Academy of Sciences, Moscow (Russia)

L. V. Al'tshuler
V. N. Subarev
A. V. Bushman
A. A. Leont'yev
P. I. Ulyakov
M. V. Shernokletov
V. Ye. Fortov

Physical Technical Institute im. A. F. Ioffe, USSR/Russian Academy of Sciences, Leningrad/St. Petersburg (Russia)

G. I. Mishin
V. P. Valitskiy
Z. V. Fedichkina
E. N. Bellendir
V. A. Stepanov
Ye. M. Drobyshevskiy
R. O. Kurakia
K. B. Abramova
N. A. Zlatin
A. A. Kuzhusko
E. L. Zil'berbrand
A. B. Pakhomov
S. I. Rosov
V. M. Sokolov
I. Ya. Pukhonto
B. P. Peregud
G. S. Pugachev
I. P. Shcherbakov
B. G. Zhukov
V. V. Speyzman
N. N. Peschanskaya

Space Research Institute, USSR/Russian Academy of Sciences, Moscow (Russia)

Yu. G. Malama
L. V. Leont'yev
I. A. Tereshkin
A. V. Tarasov

Strength Problems Institute, Ukranian Academy of Sciences, Kiev (Ukraine)

G. V. Stepanov
E. G Safarov
A. M. Ul'chenko
A. A. Avetov

Technical Physics Scientific Research Institute, Chelyabinsk (Russia)

M. M. Rusakov
R. I. Ivanov
M. A. Lebedev
B. K. Shaydullin
S. G. Shpak

Table III.3

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— HYPERVELOCITY IMPACT CAPABILITIES (cont'd.)

Theoretical Physics Institute im. L. D. Landau, USSR/Russian Academy of Sciences, Chernogolovka (Russia)

- A. V. Anisimov
- A. B. Konstantinov
- B. A. Demidov
- S. G. Sugak
- A. V. Bushman
- N. A. Inogamov
- R. Z. Sagdeyev
- G. I. Kanel'
- L. I. Rudakov
- V. Ye. Fortov
- E. I. Andriankin

Affiliations not identified

- V. V. Boyarevich
- E. V. Shcherbinin
- A. P. Nikolayev
- V. A. Gridneva
- A. B. Kiselev
- V. F. Spiridonov
- A. A. Kalmykov
- V. N. Kondrat'yev
- A. K. Mukhamedzhanov
- V. F. Agarkov
- A. I. Chaikovskiy
- G. M. Bulantsev
- L. V. Yefremova
- V. V. Kobelev
- M. V. Yumashev
- Yu. G. Federova
- I. V. Nemchinov
- V. B. Mintsev
- T. N. Nazarova
- A. Yu. Chudnovskiy
- A. I. Korneyev
- V. G. Trushkov
- V. I. Postnov
- S. M. Bakhrakh
- A. N. Bogomolov
- A. I. Petrukhin
- Yu. B. Zapobogets
- A. K. Rybakov
- L. G. Lebedeva

Table III.4

KEY SOVIET RESEARCH PERSONNEL IN HYPERVELOCITY

Atomic Energy Institute im. I. V. Kurchatov, Moscow, Troitsk (Russia)	
V. F. Demichev	Railgun, tokomak
Chemical Physics Institute, USSR/Russian Academy of Sciences, Chernogolovka (Russia)	
L. V. Al'tshuler	Equation of state, vapor, plasma
A. F. Akkerman	Lasers, hypervelocity
S. I. Anisimov	Equation of state, impact test, debris
V. A. Agureykin	Damage modeling
A. V. Bushman	HE drivers, equation of state, plasmas
V. Ye. Fortov	Theory, experimental equation of state, plasmas, HE drivers

Table III.4

KEY SOVIET RESEARCH PERSONNEL IN HYPERVELOCITY (cont'd.)

Chelyabinsk (Russia—facility not identified)	
M. M. Rusakov	Hypervelocity impact
Electrotechnical All-Union Institute, Istra (Moscow Region—Russia)	
V. N. Bondaletov	Inductive launcher
T. G. Petrov	Inductive launcher (theory)
T. G. Vlasova	Inductive launcher
High Temperatures Institute, USSR/Russian Academy of Sciences, Moscow (Russia)	
Ye. N. Avrorin	Equation of state
V. Ye. Fortov	Computational analysis
Ye. F. Lebedev	Railgun development
V. F. Lebedev	Railgun development
S. L. Leshkevich	Proton beam, impact simulation
Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)	
A. A. Deribas	Jetting, penetration
S. K. Godunov	Jetting, penetration
L. A. Merzhiyevskiy	Ballistics, jetting impact
G. A. Shvetsov	Railgun development
V. M. Titov	Ballistic, jetting
Krasnoyarsk State University, Krasnoyarsk (Russia)	
S. I. Fomin	Jets, ballistic applications
V. I. Kirko	Jets, ballistic applications
Physical Technical Institute im. A. F. Ioffe, USSR/Russian Academy of Sciences, Leningrad/St. Petersburg (Russia)	
Ye. M. Drobyshevskiy	Railgun development
G. I. Mishin	Launchers, application
N. A. Zlatin	Material failure, diagnostics
Theoretical Physics Institute im. L. D. Landau, USSR/Russian Academy of Sciences, Chernogolovka (Russia)	
I. A. Iogamov	Debris effects

Table III.5
MAJOR SOVIET PUBLICATIONS IN HYPERVELOCITY *

L. A. Merzhiyevskiy, V. M. Titov, Yu. I. Fadeyenko, and G. A. Shvetsov	"High-Speed Launching of Solid Bodies," 1987
L. A. Merzhiyevskiy and V. M. Titov	"High-Speed Collision," 1987
V. P. Muzychenko and V. I. Postnov	"Comparative Tests on Materials in High-Speed Impact with Penetration (Review)," 1984
N. A. Zlatin and G. I. Mishin	*Ballistic Ranges and Their Application in Experimental Research*, 1974
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CHAPTER IV
MATERIAL RESPONSE IN HIGH-VELOCITY IMPACT AND PENETRATION

A. SUMMARY

The abundance and quality of recent Soviet literature on dynamic material properties indicate a clear recognition of the key role of material response models and materials characterization data in satisfactorily describing and advancing applications in high-velocity impact and penetration mechanics. This recognition is confirmed by the significant number of scientists who have chosen to work in both the field of impact and penetration mechanics and in the field of dynamic materials characterization. The quality of Soviet research has been good and generally comparable with work in the West in the same period. However, some notable areas of mainstream Soviet interest have been largely ignored in the West. Similarly, there are some unexpected gaps.

A curious difference has been the continued Soviet reliance on explosive flyer-plate systems to perform controlled equation-of-state and material response experiments. These methods have been largely abandoned in the West in favor of light gas and propellant gun launch systems. Similarly, variable capacitance transducers for the measurement of free-surface motion in shock-compression studies have been the most common Soviet shock profile diagnostic, whereas Western technology now primarily relies on laser interferometry or high-resolution in-material diagnostics. Lack of timely access of some of the Soviet laboratories to the necessary advanced electronic and mechanical components may explain their lack of progression.

On the other hand, there have been some clever state-of-the-art applications of such tools as velocity interferometer technology in Soviet experimental research. The studies of Yu. I. Meshcheryakov, S. A. Atroshenko, and coworkers, in which profile irregularities and contrast variations in velocity interferometry data were used to investigate heterogeneous deformation effects in the compressive shock process, are one example.

Research in impact and penetration mechanics in the successor states of the former Soviet Union is likely to continue to produce examples of excellence in the solution of problems through innovative analytic methods. Large-scale computer solutions are not always the optimal approach, and the significant thread of Soviet study that focuses on characterization of application-specific material response properties is an attractive alternative. For example, the strength term introduced in various extensions of the Lavrent'yev hydrodynamic theory of penetration has provoked considerable favorable experimental and theoretical attention. At higher penetration velocities, where much Western literature blithely assumes transition to hydrodynamic behavior, Soviet studies have seriously addressed issues of compressibility, theoretical strength, dissociation, and ionization. The gap here is not major, however.

Advanced ultra-high-pressure and -temperature equations of state for the multiphase description of matter—essential to the analysis of hypervelocity impact phenomena—do not appear to have been widely discussed in the published Soviet literature. Several researchers, however, have alluded to "broadly applicable" equations of state, and it is believed, through discussions and unpublished presentations, that capabilities in this area are on a par with the best in the Western literature. A 1984 book by V. Ye. Fortov and I. T. Yakubov, however, may have provided an opening for accessing this research.

Constitutive models for computational applications to describe material deformation more closely tuned to threshold penetration effects (plugging, perforation, spall) also are comparable to Western efforts. Sophisticated kinetic treatment of tensile fracture and failure appears to have been more widely implemented over various Soviet laboratories than in the West. On the other hand, treatment of compressive yield and flow has generally been somewhat simpler. Thermal softening and adiabatic shear have usually been treated rather cursorily. Quite advanced computational models for porous materials have been in use. Models of computational level for dynamic deformation and failure in high-strength brittle materials such as ceramics have been noticeably absent.

Although apparently not yet widely influencing current application computational models in the former Soviet Union, extensive fundamental investigations of dynamic material strength in progress could be expected to impact the next generation of material response models. Ultimate material strengths expected in impact or penetration applications in certain materials have been addressed through lattice dynamics calculations and detailed molecular potential analysis. Dislocation dynamics methods have been actively pursued. Critical issues of deformation heterogeneity and turbulence in solid dynamics flow have received attention through high-resolution experiments and advanced theories. Soviet results have been comparable with, but do not necessarily duplicate, similarly focused efforts in the West.

Research in dynamic fracture and fragmentation continues to build on earlier work. Material parameters specific to the kinetic spall models have been acquired for a number of metals. An advanced anisotropic statistical kinetic crack model has been developed and applied to problems of transient failure of solid structures. The model parallels or is ahead of similar efforts in the West. Theories of dynamic fragmentation have drawn on earlier efforts in the West.

Recent Soviet attention has been paid to "superdeep" penetration (microparticle penetration) and anomalous diffusion (atomic penetration). These efforts lend stark evidence to the nonscalability of macroscopic material response models, and research in the former Soviet Union has currently been focused on identifying the underlying responsible material properties. Potentially important consequences can be expected from these investigations.

An area of current research in the former Soviet Union is the application of the science of synergetics of deforming media to the transient response of material in high-velocity interactions. Corresponding research in the West appears to be largely absent. The subject examines the turbulent fractal nature of dissipative structures within high-rate flow and shock deformation, and offers a fresh and modern look at a classical subject. Quantum and atomic properties fall easily into the framework. These efforts can only serve to stimulate and broaden the field. The kinetic approach to fracture based on the dilaton theory of matter fits naturally into the science of synergetics.

Finally, although it was not a principal topic for this assessment, the subject of advanced materials is a natural extension of material response issues in impact phenomena, and some relevant Soviet research was identified in this area. In particular, fairly extensive development and mechanical response research on high-strength ceramics and ceramic mixtures have been observed. Soviet researchers developing ceramics and those performing terminal ballistics studies appear to have interacted relatively closely, with some workers skirting both areas.

B. INTRODUCTION

Prediction of the consequences of the high-velocity interaction of a projectile with a stationary body requires knowledge of the motions and properties of the materials involved. Such requirements can be minimal, however. The depth and velocity of penetration of an elongated body into an infinite medium (both materials being incompressible and hydrodynamic) are readily determined through elementary momentum balance principles. Only the initial velocity and densities of the materials involved are required.

In application, limitations due to the ideal nature assumed for the materials are soon encountered. If the material exhibits resistance to shear, then the hydrodynamic predictions are increasingly in error as the velocity is lowered. If the materials show finite compressibility under pressure (elasticity, phase transformation, porosity), then errors are encountered at high velocities. Hence, models based on more detailed knowledge of material responses are needed to maintain predictive accuracy in light of the more complex properties of real materials.

As a broader range of impact phenomena is encountered (cratering, perforation, ricochet, microparticles), or as the list of prediction requirements is extended (crater dimensions, ballistic limits, size and trajectory of debris ejecta, melt or vaporization), the need for expanded material property data and corresponding response models deepens.

Soviet studies of high-velocity impact phenomena and related material property studies appear to have maintained an impressive balance. Many of the workers have spanned both fields, addressing the mechanics of high-velocity impact and penetration, as well as material property description and modeling. Material property investigations have spanned the full range of requirements, from parameter studies specific to particular analytic impact or penetration models, to fundamental physical and material science studies whose products are broad-ranging constitutive models for computational analysis of complex high-velocity interaction phenomena.

Most of the recent Soviet literature identified and reviewed for this assessment falls naturally into several areas that serve to identify major topics in the discussion that follows in Section IV.C.

- Soviet research publications have occasionally discussed some of the experimental loading methods and diagnostics used to acquire dynamic material property data; current methods and directions in this area are summarized below.

- Investigation of the equation of state of matter, both at a fundamental level and for development of constitutive models for numerical simulation, has been an active area of research and is a major topic in this discussion.

- The dynamic compressive shear strength of solids, including theoretical strength, adiabatic shear, and dynamic viscosity, has been addressed in a broad base of recent Soviet literature and provides the next topic.

- Dynamic fracture and fragmentation have continued to receive attention, and advances have recently been made in this area—the topic addressed next.

- Some recent Soviet research has uncovered relevant material property information through unusual methods or new theories that did not fall naturally into the obvious categories. These issues include deformation luminescence effects, anomalous micropenetration phenomena, and the molecular theories of dilatons and synergetics. These topics are treated in a subsection on special effects and fundamental studies.

- Finally, although not a principal objective, some Soviet literature revealed relevant research in advanced materials development or application and is summarized in the last topic.

C. DISCUSSION

1. Experimental Methods and Diagnostics for Materials Testing

The basis of dynamic material property modeling for analysis and computation is controlled experimental loading methods and diagnostic techniques for measuring material properties and validating models. Important advances have been noted in material properties testing in the recent Soviet literature; however, most of the recent literature also indicates that testing techniques developed in the 1960s and 1970s, perhaps with some improvements, continue to be used. Although explosive systems are still commonly used for dynamic material response testing, a range of gun launch facilities has expanded testing methods at a number of laboratories. Time-resolved instrumentation, including capacitance transducers, manganin gages and, more recently, velocity interferometry, has been routinely used. Some novel applications of the latter method have been reported (Meshcheryakov et al., 1988). High-speed radiography or photography has been used in much of the ballistic work. Optical pyrometry and thermocouples have been used to measure shock and transient temperatures.

a. Explosive Methods

To investigate the dynamic material properties of solids, Soviet laboratories have developed a broad range of impulsive loading and diagnostics equipment. Explosives are still used to create controlled shock-compression states in materials (Trunin et al., 1988), and explosive methods have been advanced to achieve a broader range of loading conditions. For example, increased pressures have been attained through explosively accelerated plates to 9 km/s (Trunin et al., 1989), and convergent explosive systems have been used to achieve special effects (Alekseyevskiy et al., 1989). Nuclear loading, until very recently, was probably still used to obtain the highest pressure equation-of-state data.

Explosive flyer systems have continued to be used at the Chemical Physics Institute in Chernogolovka to investigate strength and spall properties of structural metals (Kanel' et al., 1984, 1987; Gluzman et al., 1985). Similarly, Novikov and coworkers have used glancing loads from sheet-explosive accelerated flyer plates to examine metallurgical consequences of spall in metals and metal alloys (Golubev et al., 1988; Novikov and Ruzanov, 1991; Bat'kov et al., 1989). Novikov et al. (1991) described several novel methods for testing materials and structures with explosives.

Gur'yev et al. (1987) used explosive loading on test samples in recovery capsules to investigate shock polymorphism in solids. This is presumably the same method used by Anan'in et al. (1987). Similar methods have been developed and used in the United States.[1]

b. Gun Launch Techniques

Light gas and propellant launch facilities have become the more common technique for investigation of dynamic solid material properties, and a number of laboratories have described capabilities in this area. Extensive work by N. A. Zlatin and coworkers at the Ioffe Physical Technical Institute in Leningrad (Zlatin et al., 1984, 1988) and G. V. Stepanov and coworkers at the Strength Problems Institute in Kiev (Stepanov et al., 1986, 1987) indicates a range of gun launch capabilities both for materials testing and terminal ballistics studies. Shock luminescence studies by Abramova et al. (1990) were performed on Zlatin's facilities. Certain shock-wave studies on metals and ceramics to impact velocities of 4 to 5 km/s suggest gun launch capabilities (Kanel' and Pityulin, 1984; Kanel' et al., 1987). Yu. I. Meshcheryakov and coworkers at the Blagonravov Machine Science Institute have used a 37-mm-diameter single-stage gas gun to perform dynamic strength and spall studies (Meshcheryakov et al., 1988; Atroshenko et al., 1989, 1990). O. A. Kleshchevnikov (1986) at the Experimental Physics Scientific Research Institute in Arzamas-16 apparently also has had a gun facility for dynamic material property testing. Kozhushko et al. (1987, 1991) have mentioned rod penetration experiments in ceramics at 7 to 8 km/s.

c. Other Dynamic Loading Techniques

Bogomolov et al. (1986) have tested the strength properties of a range of metals using the Taylor impact method. Analysis of the data employs the length reduction

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[1] R. A. Graham and A. B. Sawaoka, Eds., *High Pressure Explosive Processing of Ceramics,* New York: Transtech, 1987.

relations developed by Wilkins and Guinan.[2] Split-Hopkinson (Kolsky) bar methods have been used by Bragov et al. (1991) to obtain dynamic properties of metals. Modified projectiles have been used to achieve different strain-rate histories.

Although a gun launch was employed, the method of plate impact on a calibrated rod warrants attention (Vashchenko et al., 1987; Stepanov and Safarov, 1988). The high-strength rod initiated plugging in the specimen plate, and details of time-resolved forces were monitored with a capacitance transducer on the rod. Strength properties under high-shear conditions were determined. The method can be compared with the "top-hat" geometry specimens tested in a compressive Hopkinson bar apparatus by Pintat et al. (1985). Exploding shell experiments have also been used to examine strength, ductility, and fragmentation of metals (Kiselev, 1991).

d. Time-Resolved Diagnostics

The variable capacitance transducer appears to have been the most popular time-resolved diagnostic technique during the period of this assessment.[3] The method measures time-resolved motion of a free surface as a shock wave emerges. In-material manganin stress transducers have also been commonly used (Gluzman et al., 1985; Aptukov et al. 1988; Zagarin et al., 1989). Bat'kov (1989) introduced manganin gages both normal and transverse to the shock direction, as well as selected arbitrary orientations, obtaining a good characterization of the dynamic strength state in the steel tested.

Velocity interferometry has recently been used in several laboratories of the former Soviet Union. Zlatin et al. (1984) described an interesting application for measuring transverse motion and wave velocities in shock-loaded polymethylmethacrylate (PMMA) rods. They also referred to work of theirs as early as 1973 in which the theory and use of laser differential interferometry was described (Zlatin et al., 1973). Kanel' et al. (1987) used laser interferometry to measure free-surface spall signals in several alloys. Further characteristics of diffused laser interferometry (VISAR) have been exploited to examine local motion in the shock-compression process (Meshcheryakov et al., 1988; Atroshenko et al., 1989, 1990). A variable laser

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[2] M. L. Wilkins and M. W. Guinan, "Impact of a Cylinder onto a Rigid Wall," *Mekhanika*, 3(1973).

[3] Kanel' et al., 1984; Kleshchevnikov et al., 1986; Razorov et al., 1987; Golubev et al., 1988.

spot size system (70 to 400 μm) was used to measure single-grain and collective-grain motion as shocks emerge at free surfaces. These researchers also used relations relating changes in contrast to velocity dispersion to assess heterogeneous motion on the microscale.[4]

Quartz gages have been used to examine compressive shock profiles in porous metals (Krysanov and Novikov, 1988). The optical lever method was still being employed to measure incipient spall levels in copper (Kozlov et al., 1984).

e. Other Diagnostic Methods

Razorenov et al. (1985) measured the "jump off" velocity of thin aluminum foils (7 to 200 μm) to determine the rise time of compressive shock waves in copper of the order of 10 to 30 ns. Abramova and Pukhonto (1989) and Abramova et al. (1990) used high-speed (image converting) photography and photodetector methods to examine aspects of shock-induced luminescence during deformation and fracture. Ballistic pendulum methods have been developed and calibrated to measure strength and energy dissipation in high-shear plugging experiments (Astanin and Stepanov, 1983; Stepanov, 1986). Flash radiography was used to assess material motions in terminal ballistics events in the work of Gorel'skiy et al. (1988). Similarly, Kovtun and Mazanko (1988) introduced radioactive tracers into target material in attempting to assess material deformations in deep penetration experiments from post-test analysis. Anomalous results apparently stimulated further studies of atomic diffusion under shock compression (Alekseyevskiy et al., 1989).

f. Temperature Effects

Molodets et al. (1989) have implemented methods to investigate spall in metals over a range from cryogenic to elevated temperatures (77 to 540 K). Related work was performed by Novikov and Ruzanov (1991) in examining the spall properties of aluminum AMg6 over temperatures of 0 to 550° C.

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[4] The latter concept has been discussed by J. R. Asay and L. M. Barker, in "Interferometric Measurement of Shock-Induced Internal Particle Velocity and Spatial Variations of Particle Velocity," *J. Appl. Phys.*, *45*, 6(1974), 2540.

Zagarin et al. (1989) employed copper-constantan thermocouples to measure temperature profiles in shock-compressed porous material in the range of 3 to 6 GPa. Temperatures of 500 to 1200° C were measured. Chervyakov and Laptev (1991) used optical pyrometry to measure temperatures in impact craters.

2. Equation of State (Constitutive Models)

Equation-of-state efforts have focused on both fundamental studies and the development of constitutive models for numerical applications. Recent Soviet emphasis on the latter has stimulated some advances in broader material response models. Considerable effort has continued to focus on problem-specific properties, however. This continued effort has followed naturally from a Soviet history of successful analytic solutions to impact and penetration problems.

The more recent Soviet literature has indicated a concerted swing toward numerical models. Very credible models focused on ultra-high-pressure equation of state, metal viscoelasticity, phase transformation kinetics, and porous materials have been described. Recent theoretical efforts have reflected the current interest in broader based material models.

a. Operational Material Properties

It has been common in the Soviet literature to adopt material properties that have quantitative application only to specific impact interaction events. For example, the hydrodynamic theory of jet or rod penetration most frequently credited to Lavrent'yev (1957) is observed to be deficient for predictive purposes in many applications in which projectile or target involve materials in the solid state. Zlatin and Kozhushko (1982) provided a pertinent tutorial that identifies the lower and upper velocity limits in which target strength and target compressibility, respectively, must supplement the hydrodynamic theory in the penetration of a rigid rod into a solid body. The strength property contribution characterizes target deformation resistance and is dependent both on application-specific details of the penetration process and projectile material, as well as intrinsic strength characteristics of the solid. Operational strength properties have been determined, for example, for the penetration resistance of aluminum and titanium alloys to copper rods (Zlatin et al., 1989). Similar studies validating the hydrodynamic theory were performed in the United States by Eichelberger,[5] and modifications were proposed to account for target and projectile strength.

Yevstrop'yev-Kudrevatyy et al. (1990) have examined the effective hardness of several steels and an aluminum alloy through experiments involving tubular penetrators using the dimensional relations of Zlatin et al. (1988). Alternative formulas for assessing effective target strength to jet penetration were proposed and tested by Kinelovskiy and Mayevskiy (1989).

Target compressibility must be included as a material property when interface penetration velocities exceed the material sound velocity (Zlatin and Kozhushko, 1982), and equation-of-state expressions for compressibility that are compatible with modified hydrodynamic analysis have been developed (Zlatin and Kozhushko, 1980).

Agureykin and Vopilov (1989) provided a representative solution method in which the incompressible plane jet penetration flow was used as a basis for a linear perturbation analysis accounting for material strength, viscosity, and compressibility. Work by Agafonov (1985, 1986) included a similar analysis with a more critical focus on the form of the viscous resistance term.

Kozhushko et al. (1987) and Izotov et al. (1985) examined the effective penetration strength of ceramic materials through relationships developed from both the modified hydrodynamic theory and a formulation based on kinetic energy and dissipative energy balance in the penetration cavity formation. They noted that the former was appropriate for penetration velocities of order 10^3 km/s. The latter captured the dominant penetration resistance at velocities approaching 10^4 km/s. Comparisons with experimental effective strength properties determined from penetration studies in B_4C, SiC, and Al_2O_3 at 7 to 8 km/s showed values close to one-half of the theoretical strength of the respective materials. Kozhushko et al. (1991) summarized this work on ceramics in a later paper and demonstrated that penetration resistance in ceramics corresponds to metal behavior at penetration velocities in excess of fracture velocities.

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[5] R. J. Eichelberger, "Experimental Test of the Theory of Penetration by Metallic Jets," *J. Appl. Phys.*, *27*, 1(1956).

Penetration experiments of copper rods into glass at velocities exceeding the crack velocity showed a high strength contribution to penetration resistance (Zlatin et al., 1988). The observed dynamic hardness of glass was consistent with the measured Hugoniot elastic limit for this material based on the common relations between penetration hardness and yield strength, and between the yield strength and Hugoniot elastic limit.

It is commonly stated that material strengths dominate the impact interaction phenomena at lower velocities, while inertial forces increasingly govern penetration rates at higher impact velocities. A refreshing examination of modifications of the Lavrent'yev hydrodynamic theory to account for material dissipation characteristics was provided by Spirikhin (1989). This work recognized the expected diminution in penetration resistance due to the dynamic hardness relative to that of inertia with increasing velocity in the modest velocity range. Included in this analysis, however, were additional barrier dissipation mechanisms activated at increasing impact velocities. Material response features such as entropy production at melt, explosive vaporization, and plasma formation, which continued to make penetration resistance due to material dissipation at increasing velocity a significant issue, were addressed. Baryon and quark transitions at ultra-high velocities were even considered.

In another application of interest, Kozlov et al. (1977) have investigated the shock attenuation properties of metals (aluminum, iron, and lead) subjected to impact by spherical particles at meteorite velocities (6 to 8 km/s). Concern with back surface spall and ejecta was a principal motive for the study. Attenuation properties were identified as the parameters in an analytic exponential attenuation law.

Shcherbak (1987) has attempted to organize and order the impact resistance of a large body of carbon and alloy steels. A particular ratio of three measured material properties—the tensile strength, elongation, and impact strength—was formed and shown through various plots to provide a useful ordering relation. The significance of this effort is difficult to assess.

b. Ultra-High Pressures

The analysis of material response at impact velocities experienced in near-Earth orbit or deep-space applications requires equations of state that are applicable over a broad range of parameters. Much of the published Soviet work has focused on models amenable to numerical simulation of high-velocity impact. Relatively unsophisticated equations of state have been used in some cases. Malama (1984), in calculating impacts from 7 to 40 km/s involving metals, minerals, and gaseous matter, used a Tillotson equation that goes smoothly to an ideal gas equation of state at intermediate densities.

Anisimov et al. (1984), on the other hand, used a detailed and wide-ranging semi-empirical equation of state to calculate impacts in the range of 60 to 80 km/s. The model was stated to have the correct asymptotic behavior in the limits of high and low densities, and high temperatures. Both experiment and quantum mechanical calculations were used to determine the approximately 20 adjustable parameters in the model. In later work, however, Anisimov et al. (1991) were content in using a two-term Mie-Gruneisen equation of state to calculate an 80-km/s impact on porous aluminum. Inogamov et al. (1991) undertook numerical simulations of ultra-high-velocity impact by microparticles. They reported investigations of the effect of several equations of state on the nature of impact ejecta, including a tabulated equation of state, a two-term Mie-Gruneisen type, and a "broadly applicable" equation of state, presumably that reported by Anisimov et al. (1984). It should be noted that, with the exception of the work by Malama (at the Problems of Mechanics Institute, Moscow), this work has all been reported by researchers from the Landau Theoretical Physics Institute in Chernogolovka.

c. Numerical Modeling

A significant effort in the 1980s focused on the development of computation-based material response models for numerical simulations of target and projectile interactions at conventional ordnance velocities.

To analyze the plugging of aluminum plates with blunt steel projectiles, Astanin et al. (1988) developed an ideal elastoplastic model based on the work, for example, of Wilkins and Guinan.[6] Plastic dissipation was treated as adiabatic, although thermal softening occurred only at material melt. The Soviet authors reported good agreement between experiment and calculation of the location and intensity of adiabatic shear bands.

Khorev and Gorel'skiy (1983) made use of a numerical material response model to perform calculations of the penetration and ring spall caused by impact of metal spheres on metal plates. The source of the model was referenced to untranslated work of Khorev and Gorel'skiy in 1981. The model described a compressible elastic-viscoplastic medium whose behavior under dynamic loading was described by a shear modulus, a dynamic yield stress, and the constants of a kinetic fracture relationship that accounted for a continuous damage evolution along with material property changes and stress relaxation. This numerical and modeling effort was continued in later investigations of Taylor impact experiments on metals (Bogomolov et al., 1986), plate perforation (Gorel'skiy et al., 1988), and impact surface damage (Dremin et al., 1986). These studies alluded to material softening due to adiabatic shear, however details of this aspect of the model were not reported.

Sugak et al. (1987) discussed a numerical model used to describe plug formation in metals at impact velocities below 1 km/s. A nonlinear pressure-volume relation described the nondeviatoric compressibility of the solid, while a pressure and plastic strain dependent yield stress characterized the deviatoric stress component. A detailed kinetic spall damage that incorporated material degradation and stress relaxation was also described. Thermal softening was included at melt. An interesting observation in the plugging calculation was the occurrence of tensile fracture damage in the intense shear zone preceding adiabatic shear softening.

Merzhiyevskiy et al. (1986) and Merzhiyevskiy and Resnyanskiy (1987) have used a somewhat different numerical modeling method to simulate explosive liner collapse and metal jet formation. A viscoelastic model of the generalized Maxwell type was used to describe compression and flow. Tensile fracture was established through a kinetic criterion based on a time integral of some power of the tensile

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[6] M. L. Wilkins and M. W. Guinan, "Impact of a Cylinder onto a Rigid Wall," *Mekhanika*, 3(1973).

overstress comparable to the Tuler-Butcher criterion.[7] Failure and stress relaxation were accomplished through a crack growth relation of the Griffith type.

Stepanov et al. (1988) have also developed a numerical constitutive relation based on a viscoelastic Maxwell model. Stress relaxation was founded on results from dislocation plasticity, and emphasis was on representing solid viscosities observed in the high-rate deformation of solids. They examined the affect of viscosity on the frontal shape and rate of penetration of an elongated striker. They numerically demonstrated that viscosity introduces a penetration scale effect, and that both shape and rate of penetration are affected by viscosity.

d. Shock Temperature

The thermal component of the equation of state, or the shock temperature, has been explicitly addressed in several studies. Noting the uncertainties that accompany the two known experimental techniques for measuring shock temperature—namely, thermal couples and optical emission—Anisichkin (1988) has developed an analytic method for calculating shock temperatures. The critical empirical observation that closes the set of analysis equations is that the ratio of the potential pressure to the total pressure is identically equal to the volume strain at sufficiently high shock pressures. It is stated that the relation was determined from investigation of a large body of shock-wave data and theoretical cold compression curves. From this relation, and reasonable estimates of specific heat, thermal energies and temperatures are calculated.

Butina (1989) proposed an analytic method for predicting shock temperatures. His method was based on a more common application of the Mie-Gruneisen equation of state and may be more applicable at moderate shock pressures. Anisichkin and Butina do not appear to be aware of each other's recent work.

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[7] F. R. Tuler and B. M. Butcher, "A Criterion for the Time Dependence of Dynamic Fracture," *Int'l. J. Fracture Mech.*, *4*, 4(1968).

Masharov and Batsanov (1989) have focused attention on the issue of heterogeneous shock temperatures. They extended earlier analysis of Grady and Asay[8] and calculated heterogeneous temperature states in metals. Al'tshuler et al. (1989) proposed heterogeneous heating as a mechanism of anomalous superdeep penetration of microparticles into metals.

e. Viscoelastic Models

Several Soviet studies have concentrated on the development of more sophisticated models addressing the dynamic viscoelastic nature of solids subjected to impulsive loading. Testing of these constitutive models has focused principally on comparisons with measured time-resolved large-amplitude wave profiles in metals.

Glazyrin and Platova (1988) developed viscoelastic governing equations for the shear stress that attempt to span a broad range of strain rates, based on concepts of dislocation motion and multiplication. Both thermal activation and viscous drag regions were accounted for. A power law was required in the viscous drag region to obtain agreement with measured wave profiles in aluminum, iron, beryllium, and copper. The study bears strong similarities to earlier work of Johnson and Barker.[9]

Kanel' (1988) used a Maxwell type model based on the viscosity law of Swegle and Grady[10] to describe compressive wave plasticity in metals. He developed a modification of Mazing's structural model to account for the microheterogeneity of real materials and successfully calculated the anomalous Bauschinger character of elastic-plastic release waves observed in solids. Merzhiyevskiy and Resnyanskiy (1984), some of whose work was discussed above, also closed the governing continuum equations of motion with a viscoelastic Maxwell relation based on concepts of dislocation plasticity. They successfully demonstrated the ability to calculate elastic precursor decay, shock-wave structure, and attenuation. Merzhiyevskiy and Kondrat'yev (1991) incorporated hyperbolic heat conduction into later thermo-visco-

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[8] D. E. Grady and J. R. Asay, "Calculation of Thermal Trapping in Shock Deformation of Aluminum," *J. Appl. Phys.*, *53*, 11(1982), 7350.

[9] J. N. Johnson and L. M. Barker, "Dislocation Dynamics and Steady Plastic Wave Profiles in 6061-T6 Aluminum," *J. Appl. Phys.*, *40*, 11(1969), 4321–4334.

[10] J. W. Swegle and D. E. Grady, "Shock Viscosity and the Prediction of Shock Wave Rise Times," *J. Appl. Phys.*, *58*, 2(1985), 692.

plastic models, concluding that the treatment of finite thermal relaxation time is necessary in high-rate impact and pulse radiation applications. This advance appears to be an important step in introducing fully coupled heat conduction models into wave codes.

f. Phase Transitions

Researchers have continued to recognize the important effects of polymorphic phase transformation in dynamic shock and penetration processes, and recent Soviet efforts in this area are noted. Breusov (1989) addressed the issue of hysteresis of phase transformation during shock compression, particularly in the ceramic materials such as quartz and boron nitride. The competing effects of large shear, and high rates of pressure and temperature, were considered. Transitions to metastable states during shock compression and release were proposed—consistent with other modern thinking on this subject. The effect of heterogeneous states on the transition in quartz was studied and coordination transformation of melt suggested for the observed knee in the shock-compressibility curve.

Gur'yev et al. (1987) have examined the influence of coolants on the retention of shock-induced phases in the shock compression of powders of the oxides TiO_2, ZrO_2, and HfO_2. This work is representative of a body of research that has been assessed elsewhere.[11] Kovtun and Timofeyeva (1989) have unsuccessfully looked for reported possible shock-compression phases in self-bonded silicon carbide (SiC with mass content of free silicon) to 83 GPa using X-ray analysis on recovered samples. A potentially important side observation was defect-produced line-broadening in tests at 46 GPa that may imply a predominance of plastic flow in the shock compression of SiC at these levels.

A novel shock-compression study by Poduretz et al. (1988) on a quartz-aluminum mixture was undertaken to investigate the effects of shear on the four- to six-fold coordination transformation in SiO_2. Results of the study were uncertain; however, comparisons of hydrodynamic states in quartz from the mixture data with

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[11] M. Ross, J. Asay, F. Bundy, R. Graham, J. F. Rogers, J. Schirber, ***Soviet High-Pressure Physics Research***, Foreign Applied Sciences Assessment Center (FASAC) Technical Assessment Report, Science Applications International Corporation, McLean, Virginia, 1982

Hugoniot data on polycrystalline quartz may provide valuable property data on strength states under shock compression—although this possible interpretation was not mentioned by the authors. Zhugin and Krupnikov (1987) have measured time-resolved profiles in quartzite with manganin gages and identified a critical compression state at approximately 20 GPa—possibly associated with the SiO_2 coordination transformation. A critical point on the quartz Hugoniot in this region has not previously been reported.

Balankin et al. (1989), with characteristic flair, have introduced transformation concepts in the shock process that go beyond the atomic structural phase transitions considered previously. They suggested the occurrence of kinetic phase transformations (KPTs) involving the formation of dissipative structures within the shock deformation process. These processes probably entail the triggering of turbulence with heterogeneous regularity in the shock front at critical stress and deformation rate states. They further proposed the existence of scaled phase transitions (SPTs)—abrupt changes in KPTs that occur as dimensions and boundary conditions affecting the transition region change. Some modern and interesting concepts were introduced in this investigation.

Zhukov et al. (1984) and Zhukov (1990) developed a thermodynamically consistent kinetic equation of state to describe dynamic phase transformations such as the $\alpha \leftrightarrow \varepsilon$ in iron and the $\alpha \leftrightarrow \omega$ in titanium. The model was used to successfully predict wave profiles in these materials. The methods were formally similar to a number of earlier studies.[12] Compression wave experiments on both high-strength steel and Armco iron by Gluzman et al. (1985) that demonstrated similar characteristics of the dynamic $\alpha \leftrightarrow \varepsilon$ transformation were important in this regard. Kozlov (1991) has identified the $\alpha \leftrightarrow \omega$ transition in zirconium at 9.2 GPa under shock conditions and noted a ductile-to-brittle transition in spall character associated with the transition.

g. Porous Materials

A variety of Soviet studies on foams and porous media have indicated an active and continuing interest in the high-velocity interaction and shock mitigation prop-

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[12] For example, D. B. Hayes, "Wave Propagation in a Condensed Medium with *N* Transforming Phases: Application to Solid-I-Solid-II-Liquid Bismuth," *J. Appl. Phys.*, *46*, 8(1975), 3438.

erties of these materials. A range of material modeling and material property studies on porous materials has been performed. Aptukov et al. (1988) developed and applied a continuum thermomechanical porous materials model with pore collapse kinetics. They were aware of at least some of the relevant work in this field from abroad. The model followed traditional formalism, although it had several original aspects. A comparable computational model for porous media was reported by Belov et al. (1988). Equation of state and strength were dependent on the material distention. Pore collapse was governed by kinetics of Carroll and Holt.[13] The model was used to evaluate the ability of porous spacers in metal laminates to mitigate spall during explosive loading.

Studies of Gvozdeva and Faresov (1986) and Kuznetsov et al. (1986) have dealt with the shock propagation properties of highly distended foams in which equation-of-state characteristics of entrained gas play a crucial role. In the first study, an incompressible solid phase was assumed, while gas within the pores was treated as ideal. Comparisons were made with shock-compression experiments on polyurethane foams. Kuznetsov et al. (1986) treated the foam as a pseudo gas in which the adiabatic index was an appropriate averaging of the condensed and gaseous phases. A ternary water-vapor-ideal gas system was considered for the materials of interest. Issues of thermal relaxation in unit cells were addressed.

Stepanov et al. (1988) have noted the similarity in certain applications of the inelastic volume change associated with shock-induced collapse of a porous medium and a structural phase change. This equivalence does have some conceptual merit. They then derived estimates for shock velocity versus pressure relations based on more elementary athermal elastic properties. The results were capable of capturing the basic features of shock compression in porous or phase transforming materials, but the model appeared to be lacking in broader predictive usefulness.

Balankin (1988, 1989b) directly addressed the penetration of a cumulative jet into a porous medium. In his unique theoretical approach, he established dimensionless groups of common physicomechanical properties (for example, dynamic strength, sound speeds, crack speeds, heat of vaporization) associated with penetrating and

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[13] M. M. Carroll and A. C. Holt, "Static and Dynamic Pore-Collapse Relations for Ductile Porous Materials," *J. Appl. Phys.*, 43, 4(1972), 1626.

porous media. He then identified specific regimes of flow that depend on the rate of penetration relative to characteristic velocities in the impact and target materials. Various features of the penetration process were calculated. It was demonstrated, for example, that a porous material could have a larger penetration resistance than a solid material of the same density. Collaborations with researchers at the Ioffe Physical Technical Institute (Leningrad) were acknowledged.

Experimental studies on porous and dispersed media have been performed. Earlier shock studies of Dianov et al. (1976, 1979) are representative. More recent investigations by Trunin et al. (1989, 1990, private communication) on porous metals, geophysical material, and ice have been providing the needed shock property data for these materials.

Nesterenko (1983) put forth the possible application of soliton dynamics to describe compacting wave motion in porous media. This proposition has been assessed recently by Miller.[14]

h. Mixtures

The experimental method of immersing a high-strength material of interest in a second low-strength material to achieve near hydrodynamic states in the shock-compression process was first attempted by Adadurov et al. (1962). The method has continued to receive attention because of the additional equation-of-state information provided. Kanel' and Pityulin (1984) have examined, under shock compression, mixtures of titanium carbide and paraffin and determined through mixture analysis the hydrodynamic behavior of TiC to nearly 50 GPa. Shock-compression studies were also performed on nickel and titanium carbide mixtures. A large viscous component of dynamic stress was inferred from the data.

Anan'in et al. (1987) investigated the shock properties of quartz-paraffin mixtures. The compressibility and SiO_2 phase change were complicated by the large shock temperature component in the paraffin. Poduretz et al. (1988) examined the shock compressibility of a mixture of quartz and aluminum. An impressive set of

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[14] L. D. Miller, "Nonlinear Mechanics of Granular Media: A Practical Application of Soliton Dynamics?" presented at Army Science Conference, West Point, Jun 1986.

data to nearly 100 GPa was provided and, as stated earlier, some rather remarkable results may be interpreted in terms of strength properties of quartz on the Hugoniot.

3. Material Strength

The transient compressive shear strength of solids is critical to the extent and evolution of high-velocity interaction phenomena, and recent fundamental studies have addressed a number of aspects of this issue. Detailed analysis of the theoretical strength of solids has been performed. Questions of adiabatic shear, deformation heterogeneity, and dynamic viscosity have also been addressed. Little research on interface friction was uncovered, however. Considerable investigations of dislocation dynamics and applications to strength in the shock state and dynamic plasticity have been pursued.

a. Theoretical Strength/Dissociation

Lazarev et al. (1984) pointed out that modification of the hydrodynamic penetration theory may be entirely inappropriate for brittle materials such as ceramics. When the penetration velocity exceeds the fracture velocity—which, depending on the estimates of different researchers, ranges from about 0.3 to 0.7 times the longitudinal sound velocity—a process of uncooperative failure would have to occur. Successive breakage of interatomic bonds would lead to complete dissociation of the "frozen" solid. Accordingly, this dissipation process must be accounted for in a model of penetration in brittle solids.

With this objective in mind, Lazarev et al. (1984), Shevchenko et al. (1984), Izotov and Lazarev (1985), and Izotov et al. (1985) investigated in detail the theoretical strength of brittle solids. Analyses of the theoretical strength were based on generalized Lennard Jones (Mie) and Morse potentials. Strength values for a number of brittle solids were reported. The effort was comparable to that of Rose et al.[15]

Izotov and Lazarev (1985) and Izotov et al. (1985) developed a theory of jet or rod penetration based on a balance of penetrator kinetic energy and dissociation energy of material in the crater cavity. It was offered as an alternative to the modi-

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[15] J. H. Rose, J. R. Smith, F. Guinea, and J. Ferrante, *Phys. Rev. B*, *29* (1984), 2963.

fied hydrodynamic theory of Zlatin and Kozhushko (1982) at penetration velocities exceeding the fracture velocity. Both theories were examined in an experimental penetration study on ceramics by Kozhushko et al. (1987). At penetration velocities of 7 to 8 km/s in B_4C, SiC, and Al_2O_3 penetration resistances were estimated to be about one half of the theoretical strength values calculated by Izotov and Lazarev (1985).

Mogilevskiy and Mynkin (1988) have used computational molecular dynamics simulations of shock-loaded solids to investigate theoretical strength issues. Their principal observation was an increase in theoretical strength with pressure at a more rapid rate than the pressure increase of the shear modulus. This observation resolved, in part, the anomalous "supercritical shear" concerns of Cowan.[16]

b. Adiabatic Shear/Heterogeneity/Turbulence

A number of Soviet researchers have noted the propensity for solids under varying conditions of dynamic loading to localize the deformation. Processes of macroscopic adiabatic shear have been reported in some cases. Heterogeneous or turbulent deformation in the shock-compression process has also been actively explored. Efforts to understand and characterize material response under such states have recently been pursued.

Aptukov (1990), in a broad review of the mechanical and mathematical modeling aspects of penetration, indicated a need for characterization of the adiabatic shear properties of metals with particular emphasis on application to blunt projectile impacts. Astanin et al. (1988) investigated processes of adiabatic shear in several aluminum alloys through blunt projectile impact. Both experiment and computational modeling demonstrated a conical surface of failure with localized shear and melting. Astanin and Stepanov (1983), however, provided data that show specific surface energies of the failure surfaces for aluminum alloys still exceed linear fracture mechanics values by two to three orders of magnitude.

Masharov and Batsanov (1989) concluded that localized slip in crystallite grains during shock compression of solids leads to transient heterogeneous temperature

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[16] G. E. Cowan, *Trans. Metallurg. Soc. AIME*, *233*, 6(1965), 1120.

states. An analysis of thermal states indicated temperatures near melt in shock-compressed minerals. It is interesting that Al'tshuler et al. (1989) proposed thermal softening associated with heterogeneous temperature processes as a mechanism for anomalous "superdeep" penetration of microparticles.

Atroshenko et al. (1990) examined particle velocity dispersion in the free-surface motion of shock-compressed metal specimens measured with differential laser interferometry. The data were interpreted as "rotational cells" or velocity irregularities whose characteristic length scales are considerably smaller than grain size and cannot be interpreted as the rotation of grains as a whole. They suggested a plastic heterogeneity or turbulence in the shock deformation process. Panin et al. (1982) and Panin (1990) noted that Taylor's system of dislocation plasticity precluded rotational deformation modes and developed a plasticity theory consistent with grain and subgrain rotation. Savenko et al. (1990) investigated further the turbulent nature of dynamic plasticity suggested by the data of Atroshenko et al. (1990) and inferred dynamic viscosity properties. Meshcheryakov et al. (1988) concluded that the velocity broadening measured in velocity interferometry profiles corresponded to the localization of shear strain with the formation of micropore chains at the microflow boundaries.

Balankin (1991) considered turbulence in the shock process through the concepts of the synergistics of deformable media. He examined the fractal structure of density fluctuations (turbulence zones) and concluded that above a critical driving stress a deforming system would take on a hierarchical multifractal turbulent structure that would optimize exchange of energy, matter, and entropy with the surrounding media.

c. Dynamic Viscosity

The concept of viscosity in the high-strain-rate flow of solids has been entrenched in Soviet research literature for a considerable period of time. The term was first used (in translation) at least as early as the oft-cited work of Sakharov et al. (1965) and has appeared frequently since then. It appears to have rather broad interpretation in the various applications considered and can become confused with the somewhat more restrictive definitions of viscosity applied by at least some of the schools of study in the West. Generally, it refers to rate sensitive shear stress and dissipation observed in the rapid deformation of matter.

In the shock compression of solids, the thickening or spread of shock waves is a measure of the viscosity of the material. The width of the shock front has been investigated at several institutions. Razorenov et al. (1987) measured the "jump off" velocity of aluminum foils of different thicknesses to establish the thickness of shock waves in copper near 10 GPa. Front thicknesses of about 10 and 30 μm at shock pressures of 10 and 7 GPa, respectively, compare well with similar work in the United States.[17] Results have been incorporated into a computational viscoelastic model for predictions of measured shock profile properties. Merzhiyevskiy (1987) introduced an integral over relaxation times in the deformation process that, when applied to steady-wave shocks, provided the thickness of the shock front. Relaxation times were established through common relations developed from Orowan's expression for dislocation dynamics. The author reported that calculated results were in reasonable agreement with shock thickness data for aluminum, copper, and iron.

Mogilevskiy (1988) noted that metallographic analysis of gradients in shock twinning near sample surfaces provided reasonable estimates of shock front thicknesses. He used computational two-dimensional lattice dynamics simulations to investigate shock front thickness and observed that active shear nucleation centers controlled the shock wave widths. The study was reminiscent of molecular dynamic simulations of shock profile characteristics by Holian.[18] Stepanov and Kharchenko (1986) determined viscosity coefficients for aluminum alloys over the strain-rate range $\dot{\varepsilon} \approx 10^3 - 10^6$ sec^{-1} from several methods including shock front thickness, elastic precursor decay, initial stages of cone penetration, and expansion of a cavity in metal. Both a minimum and a maximum were noted in the viscosity versus strain-rate relation over this range. Meshcheryakov et al. (1988) examined non-steady wave

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[17] J. W. Swegle and D. E. Grady, "Shock Viscosity and the Prediction of Shock Wave Rise Times," *J. Appl. Phys.*, *58*, 2(1985), 692.

[18] B. L. Holian, "Modeling Shock-Wave Deformation via Molecular Dynamics," *Phys. Rev. A.*, *37*, 7(1988), 2562.

propagation in aluminum alloys, interpreting the transition to steady state in terms of a viscosity controlled Bland criteria.[19]

As noted earlier, Atroshenko et al. (1990) have developed a technique for determining local granular and subgranular motions from the dispersion in free-surface velocity interferometry data. From data on steels, this motion was interpreted as excitation of grain vibration, and viscosity coefficients were established from the rate of damping. This analysis of viscosity in the shock compression of steels was further extended by Savenko et al. (1990). Recall that Kanel' and Pityulin (1984) also interpreted anomalous results in the shock compressibility of titanium carbide and nickel mixtures in terms of a dynamic viscosity.

Kiselev (1991) found that a viscous flow law adequately modeled the expansion of explosively loaded shells, although a viscosity dependent on both strain and strain rate was required.

d. Friction

The issue of friction between striker and impact media in a high-velocity interaction event was discussed briefly in a review of penetration mechanics by Aptukov (1990). He noted one study in which friction appeared to have no influence in a dynamic penetration event. He suggested, however, that insufficient study of this effect has been performed considering the significant role of friction in the case of static penetration.

e. Strength in the Shock State

The increase in the shear strength of solids when in the shock-compressed state, due either to the confining pressure environment or the shock-induced deformation defect structure, has been a difficult effect to understand and adequately model. Recent studies by Bat'kov et al. (1989) have addressed this topic. Manganin gages were used to measure longitudinal and transverse stresses in copper, aluminum, and steel. The Soviet researchers analyzed their own and other data to determine shear

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[19] A similar analysis was performed by J. W. Swegle and D. E. Grady, in "Shock Viscosity and the Prediction of Shock Wave Rise Times," *J. Appl. Phys.*, *58*, 2(1985), 692.

strength and elastic properties as a function of pressure in the shock-compressed state. The dynamic yield was generally observed in the Soviet studies to increase significantly with shock pressure and then drop dramatically as melt was approached. Recent comparable work in the West[20] was noted by the Soviet researchers.

f. Dislocation Dynamics

In the Soviet literature, the theoretical foundation of dislocation dynamics does not appear to have played as dominant a role in describing plasticity in high-rate and shock loading of solids as has been observed in the Western literature. In Soviet work, it has frequently been subservient to, or noted as a consequence of, other theoretical approaches, such as the synergetic theories of Balankin (1989) or the dilaton description of plasticity (Vorob'yev, 1988). There have been, however, some competent theoretical and analytical efforts based on dislocation dynamics that are comparable with current research in the West.

Merzhiyevskiy (1989) and Merzhiyevskiy and Tyagel'skiy (1988, 1991) have made a careful study of dislocation dynamics and its applications to plastic wave propagation and spall. Relations have been developed within the context of Maxwell-like viscoelastic models that have accounted for thermally activated and viscous drag-limited flow, with expressions for dislocation multiplication and hardening. Relations have generally been based on the developments of Gilman.[21] Results were used to address both shear strengthening and softening in the shock-compression profile. Stepanov and Kharchenko (1985, 1986) developed a model based on dislocation mechanics broadly applicable over a range of strain rates. The relationship, which was based on separate characteristic times for residence at, and glide between, dislocation pinning points was reminiscent of the model described by

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[20] For example, J. R. Asay, T. G. Trucano, and L. C. Chhabildas, in *Shock Waves in Condensed Matter–1987*, Eds. S. C. Schmidt and N. C. Holmes, Elsevier Sci. Publisher, 1988, 152, and

L. C. Chhabildas and L. M. Barker, in *Shock Waves in Condensed Matter - 1987*, Eds. S. C. Schmidt and N. C. Holmes, Elsevier Sci. Publishers, 1988, 152.

[21] J. J. Gilman, *Appl. Mech. Rev., 21*, 8(1968), 767.

Follansbee et al.[22] The model was successfully used to describe elastic precursor decay in steel. Glazyrin and Platova (1988) developed another dislocation plasticity model encompassing both thermal activation and dislocation drag regimes to describe compression shock-wave evolution. The model differed from Merzhiyevskiy's in the explicit power law relation for viscosity at high strain rates.

Mogilevskiy (1988) explicitly tested the Orowan equation relating mobile dislocation number and velocity to the plastic shear strain rate, experimentally and in lattice dynamic simulations, for consistency of the dislocation density that accounts for plastic flow. It was generally concluded that dislocation rearrangement and decrease in density occur after shock passage.

g. Dynamic Plasticity

Vashchenko et al. (1987a) reported strength versus strain-rate data for several steels, emphasizing a dramatic increase in strain-rate sensitivity above 2 x 10^3/s. The high rate test may have been performed with the unusual method of plate impact on a strain gaged rod method described in Vashchenko et al. (1987b), although this was not made clear.

Kiselev (1991) examined the dynamic ductility of metals through analysis of explosively expanding cylinders. An observed ductility maximum at about 7 x 10^4/s was explained within a two-stage model that accounted for defect production to a critical size and viscous ductile pore growth. A strong dependence of strength on strain rate above about 10^5/s was also required for the steel tested.

The anomalously high ductility experienced in the shaped-charge jetting of metals was considered by Krasnoshchekov et al. (1990). They suggested structural superplasticity, but also considered the energetically excited and locally heated states of grain boundaries necessary to accommodate the large deformations. Larin and Perevezentsev (1990) also critically examined the nature of superplasticity in high-rate deformation.

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[22] P. S. Follansbee, G. Regazzoni, and U. F. Kocks, "The Transition to Drag-Controlled Deformation in Copper at High Strain Rates," *Mechanical Properties at High Rates of Strain, 1984. Proc. III Conf. on Mechanical Properties of Materials at High Rates of Strain, Oxford, 9-12 Apr 1984,* Ed. J. Harding, Conf. Ser. No. 70, Bristol/London: The Institute of Physics, 1984.

4. Fracture and Fragmentation

Recent research on dynamic fracture and fragmentation in the former Soviet Union has continued to extend considerable earlier work in this area. Time-resolved spall measurements, principally on metals, have broadened the base of data for the commonly used kinetic models. Soviet researchers have also examined temperature and metallurgical effects on spall phenomena. At least one Soviet research effort has measured fracture toughness in controlled impact experiments, and other Soviet groups have been exploring the concept of failure waves in brittle solids. Dilaton theories have provided a fundamental framework for recent Soviet kinetic fracture models, and global energy principles have been used to formulate failure criteria and make fragment size prediction.

a. Spall Strength

Extensive measurements of spall strength were performed in the Soviet Union during the 1970s, and the intensity of the effort has continued, with broader emphasis on temperature, strain rate (pulse duration), and material preparation effects.

Kanel' et al. (1984) reported on the spall properties of the extensively studied AMg6 aluminum alloy. Spall strength and the work of rupture were determined from capacitance gage free-surface velocity, and the dependence of spall strength on strain rates was noted—a feature of dynamic strength explored in US studies at about the same time. Golubev et al. (1988) revisited the spall behavior of AMg6 aluminum, and reported differences between bar and sheet stock along with temperature and strain-rate sensitivity.

Gluzman et al. (1985) examined the spall properties of high-strength steel both parallel and perpendicular to the rolling direction, noting about a 15-percent reduction for the latter. Analysis of time-resolved profile data in this work demonstrated an excellent understanding of material property effects on wave profile features. Kleshchevnikov et al. (1986) have also investigated the rolling direction dependence of spall strength in a number of structural steels and saw similar dependences. They also reported an increase in spall stress with increasing indentation hardness of the steel. Kanel' et al. (1987), in examining shock-amplitude dependence of titanium and aluminum alloys and steel, found little sensitivity.

Kozlov et al. (1984) investigated spall in copper by thin-pulse propagation through a wedge-shape specimen—a method in common use in the United States during the 1970s. They investigated spall damage as a function of pressure gradient of the tensile pulse. More recent Soviet spall strength experiments have been performed on tantalum-tungsten alloys (Golubev et al., 1988) and magnesium-lithium alloys (Golubev et al., 1990). This research has correlated static failure data and included extensive metallurgical examination of spall damage mechanisms.

Meshcheryakov et al. (1988) measured the spall strength of several aluminum alloys with velocity interferometry and compared ratios of dynamic to static strength. They found that higher ratios were obtained for alloys that showed less proclivity toward shear localization as indicated by velocity dispersion in the interferometer data.

Kostin and Fortov (1991) studied the very high strain rates (10^7/s to 10^8/s) spall strength of aluminum through numerical simulation of the pulse interaction and dynamic tension processes. They proposed that careful treatment of elastic-plastic properties of the material along with kinetics of the failure process justified such extrapolation.

b. Temperature Effects

Golubev et al. (1988) examined the spall characteristics of AMg6 aluminum at ambient temperature and at 500°C. Reduction of spall strength with temperature was observed along with qualitative observations on increased ductility within the damage microstructure. Similar temperature studies of spall by Golubev et al. (1985) were performed on several metals including Armco iron. Molodets et al. (1989) conducted an extensive study of the spall properties of Armco iron over the temperature range of 77 K to 540 K, including capacitance probe free-surface velocity measurements and microstructural analysis. Reduction in spall-zone thickness and a weak linear dependence of the spall strength on temperature were explained through a theory of thermal activation of subcritical cracks at sites of large local stress brought about by the interaction of moving dislocations. This work represents a very thoughtful exploration of the spall process.

c. Brittle Fracture/Failure Waves

Soviet researchers have frequently studied the influence of microstructural characteristics of fracture in metals on brittle vs. ductile spall. For example, metallurgical features of brittle spall fracture in iron were described in detail by Molodets et al. (1989), and transition from ductile to brittle spall fracture through the $\alpha \leftrightarrow \omega$ transition in zirconium was discussed by Kozlov (1991). Such studies are comparable with recent investigations of metal spall in the United States by Zurek and Gray.[23]

Specific references to spall studies in inherently brittle materials (ceramics, glass) were not found in the Soviet literature reviewed for this assessment. However, various Soviet researchers have implicitly recognized the importance of compressive brittle fracture processes during high-velocity penetration in such materials. Zlatin et al. (1988) discussed a transition from compressive fracture to plastic yield in penetration experiments in glass as velocities pass through the maximum velocity of brittle crack growth. Galanov et al. (1989) also considered the limiting speed of a brittle "failure front" or failure wave in an analysis of rod penetration in ceramics. Balankin (1988) also included a limiting fracture wave velocity in his analysis of penetration in brittle materials, and Kanel' (1991) found experimental evidence for such a feature in shock-compression tests on glass. Bakun et al. (1986) noted that the ability to support a sustained fracture wave could be material dependent and was related to the storage of elastic energy in the competent microstructure. The concept of brittle failure waves and the accompanying transition behavior in penetration phenomena have not received significant attention in the West, although recent work of Brar et al. [24] suggests accelerated interest in mechanisms of brittle failure under shock and penetration conditions.

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[23] A. K. Zurek and G. T. Gray, III, "Dynamic Strength and Strain Rate Effects on the Behavior of Tungsten and Tungsten Alloys," *J. de Phys. IV, Colloque C3, Suppl. au J. de Phys. III, DYMAT 91, III Int'l. Conf. on Mechanical & Physical Behavior of Materials Under Dynamic Loading, 14-18 Oct 1991, Strasbourg, France, 1,* (1991), C3-631.

[24] N. S. Brar, Z. Rosenberg, and S. J. Bless, "Spall Strength and Failure Waves in Glass," *J. de Phys., Coll. C3, Suppl. au J. de Phys. III, DYMAT 91, III Int'l. Conf. on Mechanical & Physical Behavior of Materials Under Dynamic Loading, 14-18 Oct 1991, Strasbourg, France, 1,* (1991), C3-639.

d. Dynamic Fracture Toughness

Meshcheryakov et al. (1990) used rear surface spall methods to determine critical dynamic stress intensity factors for crack arrest in both normal and shear modes for several grades of steel. Results were compared with a relation attributed to an untranslated article by Panasyuk and Andreykin and referenced therein based on standard mechanical properties and material structural parameters. Good agreement was noted. The technique appears comparable to methods developed by Clifton and coworkers at Brown University.

e. Kinetic Models

Kinetic models of dynamic tensile fracture, in a continuum or microstructural framework, describe time evolution of the nucleation and growth of spall damage. Such models are coupled to the instantaneous stress state and allow for stress relaxation as spall proceeds to completion. These models have received considerable attention in the former Soviet Union during the past decade and currently appear to be routinely used in computational simulation of high-velocity interaction.

At least some of the concepts Soviet researchers have commonly used in computationally based kinetic spall models appear to have originated at the Chemical Physics Institute in Chernogolovka. Sugak et al. (1987) provided a reasonably clear picture of a kinetic model in which the growth of an isotropic crack or damage volume was governed by relations including the current damage volume and the maximum principle stress. The stress and elastic moduli were, in turn, degraded through a function of the damage volume strain. Calculations with the model provided good simulations of blunt metal projectile penetration near threshold velocities. Ni and Fortov (1990) have reformulated this kinetic model to account for viscoelastic response and finite deformations. The development attempted to maintain a thermodynamically consistent framework. Kanel' et al. (1984) have measured kinetic parameters appropriate for this model on AMg6 aluminum alloy. Kanel' (1988) used the same kinetic model to describe time-resolved spall velocity profiles in high-strength steel. Khorev and Gorel'skiy (1983) implemented a version of the same model to calculate rear surface ring spall in plate perforation experiments.

Ruzanov (1984) and Novikov and Ruzanov (1991) described a kinetic model similar to the nucleation and growth models of Curran and coworkers.[25] The spall model of Belov et al. (1988) based on the kinetics of ductile hole growth is also worthy of note. Compression of porous media was governed by Carroll and Holt kinetics,[26] whereas growth of porosity was governed by a viscous law depending on tensile pressure and the current state of distention. A critical porosity of 0.3 determined fracture, and stresses were reduced to zero.

A somewhat different approach to kinetic spall was proposed by Merzhiyevskiy (1989). A "lifetime" or incubation time for dynamic fracture based on dislocation mechanics was determined for both thermal activation and dislocation drag regimes. A damage growth criterion for variable stress conditions was determined by a time integral of the inverse incubation time Merzhiyevskiy (1987). Degradation of material strength was governed through a Griffith criterion and a stress-dependent crack velocity.

Morozov et al. (1990) presented a kinetic failure concept that appeared to generalize spall criteria similar to Tuler-Butcher[27] expression. This work does not seem to be in the mainstream of current spall failure modeling.

f. Statistical Microfracture Models

A statistical thermodynamic model of a solid with microcracks has been developed in a series of papers.[28] The model treated the anisotropic tensor accumulation of microfractures and appeared to have originally been developed to address quasistatic fracture (creep, fatigue). In the later work, however, it was used to analyze dynamic fracture and spall phenomena. The statistical model, with considerable sophistication, treated the subcritical stage of nucleation and growth of weakly interacting microcracks, the critical stage at which threshold crack evolution (insta-

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[25] For example, D. R. Curran, L. Seaman, and D. A. Shockey, "Dynamic Failure in Solids," *Physics Today, 30,* 1(1977).

[26] M. M. Carroll and A. C. Holt, "Static and Dynamic Pore-Collapse Relations for Ductile Porous Materials," *Appl. Phys., 43,* 4(1972), 1626.

[27] F. R. Tuler and B. M. Butcher, "A Criterion for the Time Dependence of Dynamic Fracture," *Int'l. J. Fracture Mech., 4,* 4(1968).

[28] Naymark et al., 1984; Belyayev and Naymark, 1987; Naymark and Belyayev, 1988, 1989.

bility) was achieved, and the supercritical stage of crack propagation and link up. Explicit analogy with explosive detonation was noted by these researchers. Numerical simulations of time-resolved wave profiles with spall were also described. The statistical fracture model was comparable in detail with similar developments by Dienes [29] and coworkers.

g. Energy Theories

Kinetic theories of spall have tended to evolve from a local or microstructural description of matter. Another complementary approach has focused on energy balance principles in the spall process in a global or integrated treatment of matter. Ivanov and Mineyev (1979) developed early expression for material failure based on Griffith-like criteria. Ivanov's work on this subject has continued recently with a unified theory of material failure (Ivanov, 1990a-b). A plot of load versus size has identified regions of brittle and ductile, controlled and catastrophic, response. His work has also addressed fracture from static to high dynamic loads. Kobelev (1990) has pursued an energy and momentum balance approach to predict fracture and fragmentation in composite materials. He extended earlier methods of Grady,[30] addressing the tensor nature of the process and energy anisotropy in the fracture process. Ivanov (1991) recently became aware of inertial energy balance theories[30] and critiqued the inertial versus elastic energy balance methods. He favored the latter.

h. Fragment Size

A common consequence of a high-velocity impact event is the particulate ejecta resulting from the catastrophic failure processes. This debris can be macroscopic, microscopic, or atomic, and may involve a change of state for the materials involved. Merzhiyevskiy's (1987) review of high-velocity collisions in space applications discusses Soviet fragmentation research that has focused on empirical statistical representations of fragment debris. These studies indicated that the Rozin-Rammler (Weibull) statistical law is applicable to impact or explosive destruction events.

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[29] J. K. Dienes, *Proc. XIX US Symp. on Rock Mechanics, Conferences & Institutes*, Vol. 51, Extended Programs & Continuing Education, New York, 1978.

[30] D. E. Grady, "Local Inertial Effects in Dynamic Fragmentation," *J. Appl. Phys.*, *53*, 1(1982), 322.

Spirikhin's (1989) observations regarding the dependence of fragmentation on the intensity (pressure and loading rate) of a shock event—in tension and in shear—in terms of increasing numbers of slip systems are particularly insightful. He identified a "morphological factor" (fragment size) that characterized the degree of reduction in a shock event, and correlated this parameter with a fracture energy per unit volume (energy balance) through melt, vaporization, and ionization.

Anisimov et al. (1984) have calculated fragment sizes in a numerical simulation of an 80-km/s impact of a microparticle on an aluminum plate. The theory of fragmentation was not mentioned. Anisimov (1991) also addressed fragment ejecta in ultra high-velocity impact events, focusing attention on the spectral velocity and trajectory distributions.

As noted earlier, fragment size predictions based on energy-balance concepts have been developed to predict anisotropic fragmentation in impulsively loaded composites (Kobelev, 1990). The principles followed earlier work in the West. An interesting, although not easily understandable, approach to size prediction in the dynamic fragmentation of solids was put forth in work by Bovenko (1983) and Bovenko and Gorobets (1987). It was based on nonlinear acoustics concepts of self-resonance crystal defects subject to forcing loads. The analysis led to a fragment-size versus pulse-energy relation that was compared with data for a number of rock materials. Similarly, Galanov et al. (1989) introduced an elastic-energy versus surface-energy balance to predict fragment size in shock-compressed ceramics.

Kiselev (1991) developed a relation for prediction of fragment size in the explosive expansion of cylinders. The theory was based on a transfer of stored elastic energy to the work of fracture, and a complex strain-rate dependence followed from the rate sensitivity of flow stress and failure strain. Reasonable comparisons were made with fragment size data for steel cylinders.

i. Dilaton Theory

A physically based theory of dynamic fracture, employing the concept of negative density fluctuations called dilatons has received considerable attention in the former Soviet Union since the early 1980s and does not have a comparable counterpart in the West. Dilatons are density fluctuations, with size on the order of a phonon mean free path, that can dissociate and nucleate microcracks in the subcritical phase of the spall process. The underlying Soviet kinetic theory of strength, which relates a failure time to the driving stress through a thermal activation process, was formulated long ago (Zhurkov and Narzullayev, 1953; Zhurkov, 1957), and was specifically applied to spall in solids by Zlatin and Ioffe (1973). Recent interest appears to have resulted from development of the dilaton concept, which contributed a physical basis for expanding the theory and provided a mechanism for extracting the kinetic parameters of the theory from more fundamental material properties. Zhurkov (1983) and Petrov (1983), who previously published together, have elaborated on the dilaton concept.

Other Soviet researchers have accepted and used the theory of dilatons. Balankin (1989) elaborated the theory in his examinations of dynamic flow and failure in solids. Sorokin et al. (1991) applied the dilaton theory to impact abrasion of solids. Vorob'yev (1988) extended the dilaton concept to yield and flow in the front of a compressive shock wave.

5. Special Effects and Fundamental Studies

Some Soviet research efforts have examined material response phenomena that cannot be described by the usual continuum models of matter. Particle and light emission during dynamic deformation are evidence of complex processes at the atomic scale. Extreme conditions of dynamic pressure-shear appear to yield excited states of matter that allow for chemical and solution reactions not achievable through other processes. Recent observations of "superdeep" penetration and anomalous molecular diffusion provide stark evidence for the nonscalability of macroscopic material response models. The science of synergetics applied to the nonlinear and turbulent processes of shock and high rate deformation has recently received active attention in the former Soviet Union.

a. Light Emission Effects

Abramova and Pukhonto (1989) and Abramova et al. (1990) have studied visible and infrared light emission from metals during dynamic flow and spall. Over a wide range of metals, light intensity was observed to increase monotonically with the ratio of the yield stress to thermal conductivity. The authors concluded that infrared emission was a consequence of heating during intense plastic deformation accompanying fracture. Visible radiation was not understood—possibly luminescence of hot electrons, recombinant radiation or triboluminescence. This research represents a recent continuation of a broader effort to evaluate a number of emission phenomena during dynamic loading, including light, ions, and neutral atoms. The work was performed on the experimental facilities at the Ioffe Physical Technical Institute.

b. Reactions and Energetic Effects Under Dynamic Pressure Shear

Alekseyev et al. (1989) and Popov et al. (1989) have continued to focus on efforts motivated by the classic work of Bridgman[31]—namely, the very fast solid-state chemical reactions or mixture-to-solution reactions that can occur under dynamic or static states of combined pressure and shear. This interesting topic has been recently surveyed[32] and will not be further dealt with here. The recent directions of work by Panin (1987) and coworkers on "highly excited states" in solids should also be considered within this context.

c. Micropenetration Effects

A recent flurry of literature in the former Soviet Union has focused on observations of anomalous or ultradeep penetration of hard microparticles (< 100 μm) into metal targets. These results have serious material property implications because of the scaling issues implied. Andilevko et al. (1988, 1990) discussed much of the phenomenon in a study of penetration of various ceramic microparticles into several metals. They noted, in particular, a selectivity effect among different particle-obstacle pairs.

Various material response behaviors have been proposed to explain the effect of superdeep penetration. Buravova (1989, 1990) proposed an opening of penetration channels due to spalling caused by wave interactions from multiple impacts of the surface. Chernyy (1987) and Grigoryan (1987) postulated mechanisms of channel

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[31] P. W. Bridgman, "Effects of High Shearing Stress Combined with High Hydrostatic Pressure, *Phys. Rev.*, *48*, 15(1935), 825–847.

[32] *Structural Bond Energy Release in Energetic Materials as New Means for Designing Nonconventional High Explosives: An Analysis of Soviet Research*, TRC-91-0003 TR, Technical Research Corporation, McLean, Virginia, Aug 1991.

fracture driven by the penetrating particles. Al'tshuler et al. (1989) proposed a transition from isothermal to adiabatic conditions in the plastic flow conditions around the penetrating body for particles smaller than approximately 100 µm. This would lead to near hydrodynamic conditions and, when coupled with a process of forced laminar flow around the object, would be sufficient to explain the observed results. Simonenko et al. (1991) proposed a process in which selected particles were picked up and carried with the shock wave created by the collective impact of the flux of high-velocity particles. The theory placed specific conditions on the thickness of the shock front relative to particle size, the shock pressure gradient, and the viscous drag on the particle. Superdeep microparticle penetration is clearly an active area of study for which a reigning theory has not yet surfaced.

An unusual example of microparticle penetration appears to have originated with the study of macroscopic jet penetration by Kovtun and Mazanko (1988). Radioactive elements were selectively positioned within a target medium with the objective of using post-test radiography to diagnose flow around the penetration cavity. Anomalous dispersion of the radio isotopes was observed. In a follow-up study, Alekseyevskiy et al. (1989) investigated shock propagation in several metals through an interface containing isotopes of carbon, iron, and cobalt. (It should be noted that the results were first presented at a seminar in Katsiveli in 1978.) It was found that radioactive atoms were transported a number of millimeters into the material—the quantity of mass transfer depending on the shock intensity and strength of atomic bonds in the substance. A clear explanation for this effect was not provided, although the relatively low transport energy of interstitial atoms in the shock front was suggested. Tsai and MacDonald proposed such an atomic transport process through theoretical studies of shocks in perfect lattices.[33] Gluzman and Psakh'e (1989) suggested such an effect is responsible for quasiliquification of crystalline solids in the flow of high-velocity penetration events. Their analysis would indicate that a low density of solitons propagating in the shock may be the carriers in the anomalous mass transport process.

The issue of anomalous transport within the shock has not been sufficiently studied in recent literature either in the former Soviet Union or in the West. The exis-

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[33] D. H. Tsai and R. A. MacDonald, "Anatomistic View of Shock Wave Propagation in a Solid," *High Temp.–High Press.*, *8* (1976), 403–418.

tence of such a phenomenon could open broad possibilities for chemical, phase composition, and metallurgical processes during shock loading.

Tomashevich (1987) investigated the penetration of a "flux of elongated rods" through variations of hydrodynamic theory. This work probably addressed issues of segmented-rod or shaped-charge jet penetration.

d. Molecular and Molecular Fluctuation Effects

Extensive recent Soviet literature in which researchers have actively proposed the science of synergetics in the behavior of dissipative structures within high-rate and shock flow[34] has offered a refreshing and modern look at a classical subject. Such efforts can only stimulate and broaden the field. The only comparable effort in the West, described in *Particle Waves and Deformation in Crystalline Solids* by Fitzgerald,[35] has been largely ignored, although some of the concepts were employed recently by Billingsley and Oliver.[36] The Fitzgerald ideas only skirted the Soviet efforts referenced above, however. Also, from acknowledgments and references, it would appear that Balankin's research was at least close to mainstream research in the former Soviet Union. Note reference to a new book written by Balankin, *Synergetics of Deformable Media* (see, Balankin, 1991).

Synergetics, as developed in the Soviet literature, involved energy and entropy production principles as they apply to dissipative structures in the high-rate deformation process. It examines the self-organization nature of such processes that are accompanied by the formation of cooperative dissipative structures on the micro-, meso-, and macroscopic scales. It does not invoke additivity, which is one weakness of the dislocation theories of matter commonly used in the West. Quantum mechanical and atomic properties are readily incorporated within this theory, as are the dilaton concepts of Zhurkov (1983) and Petrov (1983). Synergetic theoretical methods have been used to examine scale effects and phase transformation (Balankin et al.,

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[34] Balankin, 1988, 1989, 1991; Balankin et al., 1989; Panin, 1990; Balankin and Ivanova, 1991.

[35] Edwin R. Fitzgerald, *Particle Waves and Deformation in Crystalline Solids*, New York: Intescience Publishers, 1966.

[36] James P. Billingsley and James M. Oliver, *The Relevance of the DE Broglie Relation to the Hugoniot Elastic Limit (HEL) of Shock Loaded Materials*, Technical Report TR-RD-SS-90-4, US Army Missile Command, Redstone Arsenal, Alabama, Mar 1990.

1989); plastic grain and subgrain rotation (Panin, 1987); dynamic fracture (Balankin and Ivanova, 1991); penetration into brittle material (Balankin, 1988); and penetration into porous solids (Balankin, 1988, 1989b).

Dilatons, as discussed earlier, are thermal fluctuations in mass density within volumetric regions with dimensions of the order of the phonon mean free path. The dilaton concept was introduced by Zhurkov (1983) and Petrov (1983) to explain subcritical crack incubation in the kinetic theory of crystals. Panin et al. (1982) provided an alternative fluctuation framework in which regions of high defect concentrations called atom-vacancy states (AVS) are created in high-gradient non-uniform fields (a shock wave is one example). Such states in highly excited solids were treated as metastable two-phase systems. In plastic flow, regions of AVS were regarded as sources of deformation defects and dislocations. The two theories are probably complimentary. Regions of AVS would, in fact, act as phonon traps experiencing rapid local heating and thermal expansion consistent with dilaton behavior.

Vorob'yev et al. (1988) has invoked the kinetic theory of dilatons to describe dynamic yield and precursor decay during shock compression. They noted the heterogeneous heating characteristics of dilatons in a deforming solid. A dynamic yield was established through the classic kinetic relation and a Weibull statistical scale relation based on the dilaton volume and sample volume ratio (approximately the shock wave length cubed).

6. Advanced Materials

In keeping with the importance of material properties in establishing the consequences of a high-velocity interaction event, it is expected that materials development efforts in the former Soviet Union would have focused on optimizing properties. Although not a complete survey, a number of Soviet reports revealed considerable efforts in this direction. Research in improved metals, ceramics, composites, foams, and layered media was reported. Soviet efforts to improve terminal ballistic performance of ceramics have been particularly active, and a number of researchers have participated in both materials development and impact performance studies.

a. Ceramics

Gogotsi et al. (1981, 1986, 1987a-c, 1988, 1989) at the Materials Science Institute in Kiev have tested the mechanical and strength properties of a broad range of monolithic ceramics (silicon nitride, silicon carbide, boron carbide, zirconium dioxide), along with a range of mixtures derived from these ceramics. Ceramics were evaluated based on ultimate strength, fracture toughness, dynamic and static elastic modulus over a range of temperatures. Grigor'yev et al. (1989), via the same methods, investigated the Al_2O_3–B_4C system and Gridneva et al. (1981) examined principally the strength and fracture toughness properties of self-bonded SiC as a function of grain size.

Kovtun and Timofeyeva (1988), also at the Materials Science Institute in Kiev, investigated the shock-pressure properties of self-bonded SiC for phase transition effects and deformation modes. Kovtun and Trefilov (1989) also investigated shock properties of polycrystalline cubic boron nitride. Kovtun, with Galanov et al. (1989), has reported research on the modeling of impact penetration of ceramic plates, and, with Alekseyevskiy et al. (1989), work in the anomalous shock-induced diffusion of radio isotopes. Vlasova et al. (1988) have examined self-bonded silicon carbide under shock compression with electron paramagnetic resonance (EPR) techniques with the objective of assessing deformation modes during high-velocity rod penetration.

Osipov et al. (1987) provided a detailed study of fracture toughness in hot-pressed boron carbide with porosity varied from near zero to 40 percent. Bubnov et al. (1986) provided useful elastic constant data on silicon-nitride-based ceramics as a function of porosity, and verified theoretical relations for the elastic constants. Kharitonov et al. (1989) examined the influence of porosity on strength in high-alumina ceramics. Static high-pressure equation-of-state data for cubic boron nitride were provided by Yakovenko et al. (1989), and Aleksandrov et al. (1990) provided corresponding high-pressure data for cubic-BN and SiC.

b. Porous Material/Layered Media/Composites

Kostyukov (1980) investigated the shock attenuation (or amplification) characteristics of a layered medium in which intermediate layers are porous material. Analytic studies showed that certain combinations could lead to shock reinforcement at the output. Belov et al. (1988) investigated a similar layered porous medium and examined spall mitigation properties. Numerical methods and advanced material models were used in the analysis. Balankin (1989b) examined the penetration properties of brittle and ductile porous media with emphasis on assessing improvements in penetration resistance for such materials. Krysanov and Novikov (1988) studied various metal and polycarbonate foams, focusing on microstructure features important to shock mitigation.

The work of Kobelev (1990) was concerned with the fracture resistance and failure modes of fiber-reinforced composites.

D. PROJECTIONS FOR THE FUTURE

In view of the current political uncertainty in the successor states to the former Soviet Union, it is difficult to speculate with any degree of certainty on the future trends of research in the present field. A large share of the materials research in penetration and impact physics is, by its nature, defense related. The present posture of the former Soviet Union suggests that funding in such areas will drop dramatically. Nevertheless, under the assumption that a measure of research continuity will be maintained, some projections of Soviet research into material properties for penetration- and impact-mechanics applications have become apparent in this assessment.

- Researchers in the former Soviet Union have made impressive advances in computer usage over approximately the past 10 years, and the development of computational material response models for purposes of assessment and development of applications in impact and penetration mechanics is playing an increasingly important role. Experimental material property studies have recently shown a shifting emphasis towards the measurement of parameters for, and the validation of, computer models. This trend can be expected to continue in the future.

- Increasingly competent and sophisticated computational material response models in both the ordinance velocity regime (Khorev and Gorel'skiy, 1983; Sugak et al., 1987; Belov et al., 1988) and hypervelocity impact regime

(Anisimov et al., 1984; Inogamov et al., 1991) will continue to be developed and used within the next few years.

- Investigations into the response of materials subjected to microparticle impact and penetration have continued unabated up to the present (for example, Al'tshuler et al., 1989; Simonenko et al., 1991). Although specific applications for this research remain unclear, the effort will apparently continue until material response issues are resolved.

- The penetration properties of porous media, either as monolithic bodies or in layered structures, have received recent energetic attention (for example, Belov et al., 1988; Balankin, 1988). Because of the potential benefits of porous materials in armor or barrier applications, materials research in this area can be expected to continue.

- Research into dynamic fracture and spall in the former Soviet Union has not been intense over the period of this assessment. Some continuing efforts can be expected, however, with principal focus on fracture properties for continuum modeling, the nature of fracture waves in brittle solids, dilaton fracture theories, and fragmentation prediction capabilities. Progress on the statistical microfracture research of Naymark and Belyayev (1989) should also continue to be of interest.

- The recent focus of a few Soviet researchers (for example, Balankin, 1989a; Panin, 1987; Vorob'yev et al., 1988) on the excited states and turbulent properties of matter in either the front of a shock wave or under other conditions of extreme strain-rate loading, represents a significant and fertile direction of dynamic materials research. The researchers publishing in these areas are aggressive and imaginative thinkers and can be expected to continue their efforts in the near future. There is reasonable potential for some breakthrough from this direction of theoretical research.

- The foregoing focus has also influenced experimental work, and the active velocity interferometry research directed at dynamic microstructure within high-rate deformation (Meshcheryakov et al., 1988; Atroshenko et al., 1990) represents an important complementary effort that should continue to be watched. The optical and particle emission studies of Abramova et al. (1990) will also support theoretical studies on the metastable excited states of matter and can be expected to continue.

E. KEY RESEARCH PERSONNEL AND FACILITIES

A merging of talents has been observed between a group at the Ioffe Physical Technical Institute in Leningrad, led, until recently, by N. A. Zlatin, and a group at the General and Inorganic Chemistry Institute in Moscow. N. A. Zlatin, A. A. Kozhushko, and others at the Leningrad laboratory have pursued rather traditional impact interaction and material property studies based on modifications of hydrodynamic theories of impact and penetration. In contrast, workers in Moscow, including V. B. Lazarev, A. D. Izotov, and others, have pursued more novel approaches to high-velocity material response and penetration. Their concerns appear to have focused on higher velocities and harder materials. They have proposed that penetration resistance due to complete atomic dissociation of the "frozen" solid may dominate the higher velocity regime. A detailed theoretical investigation of the ultimate (or theoretical) strength of solids, spanning a number of papers over several years, has been pursued.

A joining of the two approaches appears to have coincided with work by Kozhushko et al. (1987), which involved an examination of the theories and high-velocity penetration experiments on ceramic materials. Research by Zlatin et al. (1988) on high-velocity penetration of glass made liberal use of the Moscow laboratory results and acknowledged discussions with Lazarev and Izotov.

An active cooperation also appears to have been established between the group at the Chemical Physics Institute in Chernogolovka under A. N. Dremin and members of the Applied Mathematics and Mechanics Institute at Tomsk State University. I. Ye. Khorev, V. A. Gorel'skiy, and others, have maintained a well-considered program in material modeling and numerical simulation of high-rate deformation. The institute at Chernogolovka appears to have provided the application stimulus and experimental research results in ordnance velocity interaction effects.

Another group at the Chemical Physics Institute that has included V. Ye. Fortov, G. I. Kanel', and S. G. Sugak has maintained an impressive program in the experimental determination of dynamic material properties, along with material equation-of-state development and computational simulation. It is interesting that I. Ye. Khorev at Tomsk State University has also published with this group.

An impressive program targeting dynamic material response for impact and penetration applications has been indicated by the work from the Lavrent'yev Hydrodynamics Institute in Novosibirsk. The leader of this effort is L. A. Merzhiyevskiy, and the program has encompassed a wide range of studies. This includes fundamental investigations and modeling of the kinetics of dislocation thermal activation and drag as it relates to dynamic flow and spall (Merzhiyevskiy, 1989); analysis and simulation of time-resolved wave-profile studies investigating dynamic plasticity, solid viscosity, and kinetics of tensile failure (Merzhiyevskiy and Resnyanskiy, 1984); and numerical material response modeling calculations of explosive-metal interaction applications (Merzhiyevskiy et al., 1987). The emphasis on high-velocity interaction of solids is demonstrated by the review by Merzhiyevskiy and Titov (1987) dealing with a spectrum of cratering and target interaction effects.

The extremely active research by A. S. Balankin and coworkers on the application of the theory of synergetics of deformable media to high-rate flow and shock deformation (Balankin, 1989a) has been noteworthy. Although very advanced theoretical concepts have been introduced, efforts have maintained a strong application orientation as exhibited by impressive studies of penetration into brittle materials (Balankin, 1988) and porous media (Balankin, 1989b). Acknowledgments to discussions with A. A. Kozhushko at the Ioffe Institute have indicated a degree of coupling with active applications research. In this vein, the recent research on excited states in matter by V. Ye. Panin and coworkers at the Strength Physics and Material Science Institute in Tomsk has also been noteworthy.

Several other noteworthy researchers and institutions in the former Soviet Union should be identified. G. V. Stepanov and coworkers at the Strength Problems Institute in Kiev have an active research program that has impressively balanced penetration mechanics and theoretical modeling of the dynamic deformation of solids. Studies by S. A. Novikov and coworkers at the Experimental Physics All-Union Scientific Research Institute in Arzamas have competently investigated material science aspects of failure and spall in a number of metals and metal alloys. Similar issues of material and structural failure have continued to be pursued by A. G.

Ivanov and coworkers, also at the Experimental Physics All-Union Scientific Research Institute. A significant achievement in the theory and computational modeling of statistical fracture has evolved at the Continuum Mechanics Institute in Perm', under the direction of O. B. Naymark and V. V. Belyayev.

Table IV.1 lists these researchers and their affiliations.

Table IV.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—
MATERIAL RESPONSE IN HIGH-VELOCITY IMPACT AND PENETRATION

Applied Mathematics & Mechanics Institute,
Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)

I. Ye. Khorev
V. A. Gorel'skiy

Chemical Physics Institute, USSR/Russian Academy of Sciences, Chernogolovka (Russia)

A. N. Dremin
V. Ye. Fortov
G. I. Kanel'
S. G. Sugak

Continuum Mechanics Institute, USSR/Russian Academy of Sciences, Perm' (Russia)

V. V. Belyayev
O. B. Naymark

Engineering Physics Institute, Moscow (Russia)

A. S. Balankin

Experimental Physics All-Union Scientific Research Institute, Arzamas-16/Sarov (Russia)

A. G. Ivanov
S. A. Novikov

General & Inorganic Chemistry Institute im. N. S. Kurnakov,
USSR/Russian Academy of Sciences, Moscow (Russia)

V. B. Lazarev
A. D. Izotov

Table IV.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—MATERIAL RESPONSE IN HIGH-VELOCITY IMPACT AND PENETRATION
(cont'd.)

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)

L. A. Merzhiyevskiy
A. D. Resnyanskiy
V. M. Titov

Physical Technical Institute im. A. F. Ioffe, USSR/Russian Academy of Sciences, Leningrad/St. Petersburg (Russia)

N. A. Zlatin
A. A. Kozhushko

Strength Physics & Materials Science Institute, Siberian Branch, USSR/Russian Academy of Sciences, Tomsk (Russia)

V. Ye. Panin

Strength Problems Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)

G. V. Stepanov

CHAPTER IV: MATERIAL RESPONSE IN HIGH-VELOCITY IMPACT AND PENETRATION

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CHAPTER V
ANALYTIC PENETRATION MECHANICS

A. SUMMARY

Analytic theory applied to deep penetration of long rods or shaped charges by researchers in the former Soviet Union continues to be developed despite the growth of computational capability. Scientists have sought to introduce new descriptions of material behavior for targets that are applicable over a broad speed range and for wide classes of materials. More solid-state physicists seem to be active in this work than in the West. One goal is to reduce or eliminate the need for adjustable parameters that appear in the one-dimensional representation of penetration. Most of the work is directed at speeds above the ordnance velocities common for long-rod penetration but applicable to shaped-charge penetration.

In many, if not most, cases where comparisons with penetration experiments are at issue, the Soviet description of the experiments has been sketchy or non-existent. Thus, it is difficult to form an independent judgment about the success of the theories.

In the case of metal targets, the now classical one-dimensional theory has been extended to include dynamic viscosity and the effects of observations showing that the plastic deformation in the target does not take place uniformly. For penetration velocities exceeding the shear velocity in the target, a new solid-state description of the behavior of the target has been introduced to replace the common representation by plasticity theory. Penetration in brittle materials above the crack velocity in the target has been studied theoretically and experimentally. Soviet researchers have shown an interest in porous materials as a way to reduce spalling. The behavior of such materials depends on the mechanisms of pore collapse during penetration, which are very complex. A theory for the penetration of shaped charges in such materials has been advanced.

Work has also been reported on attempts to explain the anomalously large penetration observed with microparticles, 10 to 100 microns in size. This matter seems to be far from settled.

B. INTRODUCTION

Analytical models of penetration continue to be important in understanding and representing penetration mechanics despite the development of elaborate computer codes. An analytical model generally provides a physical picture of the mechanics of penetration and can often identify the functional relationships of the key material and dynamic parameters, which is very useful for engineering application. In other cases, analytic models provide a useful way to represent experimental results at velocity ranges and in classes of materials not yet accessible with computer codes. At the same time, there are considerable difficulties in developing an analytical model that can represent all of the complicated phases of the projectile target interactions for different classes of materials over a wide speed range.

A major effort has focused on the development and interpretation of long-rod (or shaped-charge) penetration models to represent the principal phase of deep penetration in ductile materials where the process is approximately steady state. Soviet researchers were early participants in this development. Analytic treatments of the transient initial and final phases of penetration lead to greatly increased complexity[1] and offer limited advantages over full computer code calculations.

More recently, penetration in ceramic targets has become technologically important. The same formal analytic description of penetration in these brittle materials has proved useful in representing experimental results, but there is, as yet, no way to estimate the target strength term that appears in the representation. At penetration velocities from, say, 1 to 2 km/s, ceramic targets are fractured ahead of the penetrator. At much higher impact velocities, the penetration speed can exceed the maximum crack velocity in the target. Under such circumstances, a significant change in the target resistance to penetration might be expected. Soviet researchers have been active in exploring this speed regime.

Analytic models have been used extensively for the representation of plate penetration by a range of penetrator shapes and material properties. Typical parameters represented are residual velocity and impulse transmitted to ductile target for

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[1] M. Ravid, S. R. Bodner, and I. Halcman, "Analysis of Very High-Speed Impact," *Int'l. J. Eng. Sci.*, 25, 4(1987), 473–482.

normal and oblique impact. The theories often do well in representing the results for classes of experiments where the physical phenomena are similar, using a limited number of empirical constants determined by experiments. The possible penetration phenomena are complex and lack the comparative simplicity of long-rod penetration. Where the penetration process has involved the punching out of a "plug" from the target, simple results have been found even for a substantial variation in the mechanical properties of the materials (Mileyko et al., 1979). Penetration is resisted by plastic deformation and/or brittle fracture of a thin cylindrical layer defining the plug. In this case, a simple phenomenological model was found to adequately represent the critical punch-through velocity as a function of the obstacle thickness (Mileyko and Sarkisyan, 1981).

Most of the Soviet work reported in the published literature has been directed toward developing a better understanding of the physics of high-velocity penetration of rods or shaped charges, as well as the physics of the formation and behavior of shaped charges themselves. Some Soviet authors have argued that the classical theory of plasticity that has been used extensively to represent viscous and relaxation effects in metals is not applicable when the penetration velocity exceeds the shear velocity in the target (Balankin, 1988). A new model was proposed that "treats the dynamics of density fluctuations . . . in a system far from thermodynamic equilibrium." There has been no counterpart to this line of investigation in the Western literature.

Recent Soviet literature has provided a number of papers concerned with a new phenomenon, the superdeep penetration of very small high-speed particles into ductile or brittle targets. It would seem that the cause of this interest, which has had no counterpart in the West, has been an extensive program of Soviet research in what is called structural bond energy release (SBER). The origin of this research was experiments on materials at very high pressures by Bridgeman in the 1930s. The combination of high pressure and shear can lead to an extremely rapid explosive decomposition of the test material. The product is claimed to be a dense flow of small solid phase particles traveling at a velocity of several kilometers a second. A few Western scientists, such as Teller, have shown an interest in the SBER phenomenon, but activity has been at a low level.

The following discussion will cover the Soviet work on long-rod and shaped-charge penetration and the new phenomena associated with the anomalous deep penetration of microparticles in metal targets. In each of these areas, Soviet researchers have been exploring problems not being pursued in the West.

C. DISCUSSION

In early work, Vitman and Zlatin (1963) used dimensional analysis to model the penetration of spheres and long rods into solid targets. The key dimensionless variable was the ratio of the dynamic pressure generated in the target to the target dynamic hardness. This formulation was found to provide a good correlation of experimental data.

Alekseyevskiy (1966) has been credited with being the first to develop an analytic solution for high-speed penetration of long rods by introducing strength terms for the penetrator and target as a modification to the hydrodynamic theory. Little seems to have been published in the Soviet literature until Ulyakov (1981) extended the analytic solutions for the representation given by Tate (1967, 1969),[2] although the problem of how to choose the dynamic characteristics of the penetrator and target was not further elucidated. About the same time, work by Zlatin and Kozhushko (1980, 1982) examined the limits of applicability of the hydrodynamic model for high-speed penetration. The lower bound, where the strength of the target material can no longer be neglected, was previously given by Tate's solutions showing the "lower velocity limit" for combinations of strength properties for the penetrator and target. However, Zlatin and Kozhushko also examined the upper velocity limit for the incompressible assumption of the hydrodynamic theory. When the penetration velocity of the interface between the penetrator and target exceeds the speed of sound in the target, the penetrator/target interface is preceded by a shock wave across which the density of the target material increases. The result is an increase in the maximum pressure on the penetrator, as compared to what would be found for an incompressible fluid. The velocities at which this becomes important for metal targets are very high, above the velocities reached in most experiments.

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[2] A. Tate, "A Theory for the Deceleration of Long Rods After Impact, *J. Mech. Phys. Solids, 15* (1967), 387-399; "Further Results in the Theory of Long Rod Penetration," *J. Mech. Phys. Solids, 17* (1969), 141-150.

The "lower velocity limit" for the hydrodynamic representation of penetration experiments with tubular penetrators was neatly demonstrated using dimensional analysis (Zlatin et al., 1989; Yevstrop'yev-Kudrevatyy et al., 1990), but this does not add to the understanding of the physical parameters used in the dimensionless parameters.

Recently, Soviet researchers have sought to extend the type of analytic representation given by the Tate theory to account for the viscosity of ductile materials, penetration in brittle materials at velocities above the crack propagation velocity, and penetration in porous materials. This requires the development of suitable macro representation of material behavior under extreme conditions.

1. Dynamic Viscosity

The familiar Tate equation for the equality of the pressure in the penetrator and target at the penetrator target interface is given by

$$p = \frac{1}{2}\rho_t U^2 + R_t = \frac{1}{2}\rho_p (V\text{-}U)^2 + Y_p$$

where V is rod velocity relative to the target, U is rate of penetration of interface into target, and R_t and Y_P are strength terms for target and penetrator. However, high-strain-rate experiments with metals have provided the basis for deducing the magnitude of dynamic viscosity terms where the viscous terms are assumed to be proportional to the strain rates in the material. Kozlov (1986) added a term of the form $\frac{1}{2}\mu\dot{\varepsilon}$, where μ is a dynamic viscosity coefficient and $\dot{\varepsilon}$ is the strain rate (U/d) for the target (d is the diameter of the penetrator) to each side of the Tate equation. According to the values of the viscosity coefficients used by Kozlov, the viscous terms are comparable to the strength terms over a substantial range of velocities. Kozlov also stated that agreement with penetration experiments was improved by the addition of the viscous terms to the Tate equation, but the theoretical-experimental comparison was not presented in his paper. One problem is that, within the limitations of this type of one-dimensional theory, "average" values for the strain rates in the penetrator and target must be used. It should be noted that viscosity may also be important in explaining certain results observed in the formation of shaped charges (Kinelovskiy and Trishin, 1980).

2. Non-Uniformities in Plastic Deformation

It is assumed in using these penetration models that the deformation of the target is adequately described on a macroscopic or "average" level. Detailed studies of strain under dynamic deformation show that there is a marked non-uniformity of material movement (Divakov et al., 1987). Barakhtin et al. (1991) reported on the target behavior observed in the penetration of compact planar shaped charges in the velocity range of 2.5 to 3.5 km/s. The deformation was described as consisting of microflows at different velocities producing a turbulent flow interaction. As a result, a "turbulent" viscosity term was added to the Kozlov representation

$$\mu_T \frac{\Delta u}{\Delta h}$$

where μ_T was the turbulent viscosity coefficient, Δu, the microflow velocity spread, and Δh, the separation of microflows; Δu and Δh were estimated from the microstructural measurements. The authors claimed, without presenting experimental data, that this representation provided good agreement with the experimental measurements of jet penetration in various materials.

3. Penetration Velocity Exceeding Shear Velocity

New theoretical considerations arise when the velocity of penetration exceeds the shear velocity in the target material. The velocity of dislocations in the classical description of plastic flow is limited by the velocity of shear waves in the material. According to Balankin (1988; Balankin et al., 1988), a new description of the kinetics of rapid deformation and fracture should be introduced. The theory is based on the framework provided by synergetics and envisions kinetic phase transitions under the non-equilibrium conditions produced by very-high-speed impact. Thus, in the very-high-speed region between the limiting crack growth rate and the longitudinal sound speed, the theory leads to expressions for the strength and viscous terms that appear in the one-dimensional equation of motion.

This synergetics-based description of the behavior of ductile materials has also been applied to the refinement of the criteria for shaped-charge jet formation and analyses of the structure of shaped-charge jets. One surprising conclusion is that physical fracture of the jet occurs when it is formed, although detection of the fracture occurs later. This early segmented condition of the jet was proposed as an explanation of observations of the destruction of a shaped-charge jet by a high-voltage electric-current pulse (Yanevich et al., 1990).

However, when the penetration velocity increases enough to exceed the sound velocity in metal targets, the liquid state in the target would be expected. Balankin (1989) also examined this extensive velocity range for penetration in brittle and porous materials. Soviet researchers have been interested in porous materials used as spacers to limit spall fracture under explosive and impact loading (Belov et al., 1988).

4. Penetration in Brittle Materials

New theoretical considerations arise when the velocity of penetration exceeds the crack velocity in the target. Soviet researchers found the strength term for the target to be of the magnitude of the experimental values of the target hardness (Zlatin et al., 1988; Kozhushko et al., 1991; Balankin, 1988). At penetration velocities below the crack velocity, targets fragment ahead of the penetrator, and the measured values of the "steady-state" resistance are much lower than the hardness of the target material, though still generally greater than the resistance term for metals. The degree of target fracture is a key variable. Zil'berbrand et al. (1989), in tests on brittle materials, demonstrated that even for the initial phase of penetration (thin plates), where the effect of the shock wave generated on target impact dominates the fracturing of the target, the targets still offered significant resistance to penetration. However, if targets that had been broken up into a fine powder by the impact of an intense shock wave were used, the penetration followed the hydrodynamic theory, and the strength of the target material was unimportant.

5. Penetration in Porous Materials

Balankin (1988) developed theories for penetration in both ductile and brittle porous materials. Different modes of pore collapse lead to different modes of penetration. For ductile materials, Balankin found that the penetration depth in a porous medium is smaller than in a continuous medium when the porous and continuous media have the same density. Much more complex results have been found for porous brittle targets. These theories are intended to apply at the very high velocities of shaped-charge jets.

6. Penetration of Microparticles

Anomalous penetration behavior apparently occurs for solid particles from 10 to 100 microns in size. Instead of penetration to depths of the order of the particle dimension, streams of these small particles have been observed to penetrate to depths up to 10^2 or even 10^3 diameters. The impact velocity is of the order of 2 km/s. Only general information has been given about the experimental conditions. Grigor'yan (1987) attributed the first observation of these phenomena to a byproduct of experiments on metal hardening by explosive action on metals. However, as described in a recent report,[3] the detonation associated with the SBER phenomenon produces a dense stream of small particles, products of the reaction, at the indicated sizes and velocities. Superdeep penetration occurs for a wide variety of materials, particles, and targets. Al'tshuler et al. (1989) reported that a strong shock wave in the target that accompanies the phenomenon has a significant influence on the number of particles showing deep penetration. After penetration, largely collapsed tracks of the particles can be detected in the targets. For some reason, or reasons, the resistance to motion in these channels is anomalously low. Quite different explanations have been offered for the observed behavior. Chernyy (1987) and Grigor'yan suggested that the channel through which the particle moves is created by cracks in the material of the target so that the interaction with the target is restricted to a small contact area. Al'tshuler suggested that local melting occurs and that the particle moves through a liquid with low viscosity. Other strange effects that are said to depend on the chemical composition of the target and the particles were reported by Andilevko et al. (1990). These explanations of the phenomena could not be further apart.

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[3] *Structural Bond Energy Release in Energetic Materials as New Means for Designing Non-Conventional High Explosives: An Analysis of Soviet Research*, TRC-91-003, McLean, Virginia: Technical Research Corporation, 1991.

It is to be hoped that at some point the detailed experimental conditions and measurements of these phenomena will be published. Apparently, a major effort involving the SBER phenomenon was directed toward the development of more powerful explosives and thus was classified. Yenikolopyan (1989) has provided a recent review of the SBER phenomenon. There may be similarities between the material behavior in SBER and the hydrodynamic mode developed by Balankin for very-high-speed impact (Gluzman and Psakh'e, 1989).

D. PROJECTIONS FOR THE FUTURE

The classes of materials of interest for armor applications have been growing. The Soviet work described here could conceivably lead to a better understanding of material properties that would provide improved resistance to high-velocity penetration. In any case, further theoretical and experimental work on the solid-state physics of penetration in the Soviet successor states can be expected. Analytic theories should continue to be essential for representing the broad range of materials and conditions that are of interest.

E. KEY RESEARCH PERSONNEL AND FACILITIES

The Soviet researchers whose work is discussed in this chapter are associated with at least 15 research organizations or universities, and their work covers a wide range of disciplines. Table V.1 lists the key researchers in analytical penetration mechanics in the former Soviet Union and its successor states, and some of the key research facilities with which they are affiliated.

Table V.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—ANALYTICAL PENETRATION MECHANICS

Applied Mathematics & Mechanics Institute,
Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)

V. S. Kozlov

Applied Physics Problems Scientific Research Institute im. A. N. Shevchenko, Minsk (Belarus)

S. K. Andilevko

Belarussian State University im. V. I. Lenin, Minsk (Belarus)

Al'tshuler, L. V.

Engineering Physics Institute, Moscow (Russia)

A. S. Balankin
G. N. Yanevich

General & Inorganic Chemistry Institute im. N. S. Kurnakov,
USSR/Russian Academy of Sciences, Moscow (Russia)

A. D. Izotov
V. B. Lazarev

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch,
USSR/Russian Academy of Sciences, Novosibirsk (Russia)

S. A. Kinelovskiy
V. M. Titov

Machine Science State Scientific Research Institute im. A. A. Blagonravov,
USSR/Russian Academy of Sciences, Leningrad/St. Petersburg, (Russia)

B. K. Barakhtin
A. K. Divakov
L. I. Slepyan

Materials Science Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)

V. I. Kovtun

Mechanics Scientific Research Institute,
Moscow State University im. M. V. Lomonosov, Moscow (Russia)

G. G. Chernyy
S. S. Grigor'yan

Table V.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—ANALYTICAL PENETRATION MECHANICS (cont'd.)

Mining Institute, Leningrad/St. Petersburg (Russia)

L. I. Slepyan

Physical Technical Institute im. A. F. Ioffe,
USSR/Russian Academy of Sciences, Leningrad/St. Petersburg (Russia)

A. A. Kozhuskho   G. S. Pugachev   I. I. Rykova
V. V. Yevstrop'yev-Kudrevatyy   N. A. Zlatin   Ye. L. Zil'berbrand

Powder Metallurgy Scientific Production Association (NPO), Minsk (Belarus)

S. K. Andilevko

Solid-State Physics Institute, Chernogolovka (Russia)

S. T. Mileyko

Strength Physics & Materials Science Institute, Siberian Branch,
USSR/Russian Academy of Sciences, Tomsk (Russia)

S. L. Gluzman   S. G. Psakh'e

Synthetic Polymers Institute, USSR/Russian Academy of Sciences, Moscow (Russia)

N. S. Yenikolopyan

Strength Problems Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)

G. V. Stepanov

(blank)

CHAPTER V: ANALYTIC PENETRATION MECHANICS
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CHAPTER VI
NUMERICAL SIMULATIONS OF PENETRATION PHYSICS

A. SUMMARY

Early Soviet work in numerical simulation of nonlinear, high strain rate, large deformation material response primarily used Eulerian hydrocode formulations. There was also a significant emphasis in investigating and modeling viscous effects. This changed during the last 10 to 15 years, as a considerable portion of the Soviet work reported use of a Lagrangian finite element formulation, unequivocally influenced by the work of Gordon Johnson (the creator of the EPIC family of codes). However, the Eulerian formulation has not been totally discarded. There are a number of examples where the early-time response was modeled hydrodynamically using the particle-in-cell (PIC) method. Then, as the deformations became computationally more manageable, the Eulerian results were mapped over to a Lagrangian grid, where the computations were continued to later times. Researchers in the former Soviet Union referred to this procedure as the method of "moving grids" or "mobile grids"; the term refers to the boundary between the Eulerian and Lagrangian grids that can move. In the Lagrangian codes, strength effects and failure have been simulated. In their modeling of material response, Soviet researchers have placed a good deal of emphasis on developing both macroscopic and microscopic failure models for the purpose of numerically simulating material failure. These models have been used extensively to examine the dynamics of projectile impact against target plates.

Names such as S. K. Godunov, N. S. Kozin, and Ye. I. Romenskiy dominated early Soviet work in numerical simulation of shock waves. In the 1980s and early 1990s, N. N. Belov, V. A. Gorel'skiy, I. Ye. Khorev, and A. I. Korneyev, among others, have emerged to the forefront of simulating impact. A. N. Dremin, G. I. Kanel', and V. Ye. Fortov often have provided the motivation for the numerical studies.

In general, numerical work in the former Soviet Union has lagged behind advances in the United States. A contributing factor to this lag has been the limitations imposed by computer hardware. There are many instances where the lack of computational power, compared to that available in the United States, has limited the ability of Soviet researchers to analyze complex problems.

Soviet researchers have adopted a number of the ideas and concepts that have been published by US researchers. These observations in no way imply that the Soviet studies have been inferior in quality. There have been a number of fairly large Soviet parametric studies performed to investigate the mechanics of impact; these have clearly been very serious studies that have provided considerable insight to penetration mechanics.

Most of the computational examples in the Soviet literature have consisted of either numerical simulations of flyer plate impacts (shock wave profiles), or short length-to-diameter (L/D) steel projectiles impacting steel target plates. No numerical simulations of long-rod kinetic energy (KE) impact were found in the translated literature, and few, if any, have appeared in the unclassified Russian literature.

Numerical simulations played a critical role in the design of shielding for the Vega spacecraft, used for the flyby of Halley's comet. Although the majority of the calculations were performed in two dimensions, sufficient three-dimensional work was conducted in order to make some assessment of three-dimensional effects. A large number of calculations were performed to ascertain the effects of impact particle size, plate thickness, plate spacing, and sensitivity to equation-of-state parameters, although only a small percentage of the computations was reported. Performed in the early 1980s, this research effort was impressive because of the ingenuity displayed in devising alternate experimental techniques to simulate impact at tens of kilometers per second, and the breadth of the numerical simulations.

A US scientist who visited the Applied Physics Institute in Novosibirsk in 1990 was given a demonstration on the state of development of parallel processing computing for solving large hydrodynamic problems. This demonstration used Soviet computers (produced with Soviet-made electronic chips) to achieve high-speed computing without the need for a supercomputer, with computational times equivalent to a Cray supercomputer. The PIC methodology mentioned above readily adapts to massively parallel architectures. Notwithstanding this demonstration of massively parallel computations, there are plenty of indications in the Soviet literature where it is obvious that there has been a considerable disparity between raw computational power in the United States and the Soviet Union.

Although Soviet interest in metal viscosity has persisted, the underlying reason for including viscous effects has changed. An experimental observable is the presence of an elastic precursor wave traveling faster than the main shock. In the 1960s, the only way Soviet researchers were able to explain this experimentally observed phenomenon was to incorporate rate (viscous) effects in their material strength models. But with the adoption of a (Western) methodology developed by Mark Wilkins for computing both the elastic and plastic deformation rates, the elastic precursor arose naturally out of the mathematical formulation without recourse to viscous effects. Ironically, though Soviet researchers did not use artificial viscosity in their codes before they adopted Wilkins' methodology, when they updated their codes they found that artificial viscosity was necessary to dampen numerical oscillations behind a shock front. Although metal viscosity was no longer required to produce the elastic precursor, Soviet researchers still placed a strong emphasis on rate effects, often interpreting these rate effects in terms of a viscosity coefficient.

B. INTRODUCTION

Hydrocodes are computer programs that have the capability to compute material response from elastic deformations through high-strain, non-linear deformations at high rates of loading. In particular, hydrocodes can be used to analyze highly dynamic problems where the loading stresses far exceed materials strengths. These loading stresses result in the generation of shock waves, large plastic deformations, and material failure.

The numerical calculation of impact, penetration, and perforation of a target by a projectile requires the simultaneous solution of the three conservation equations—mass, momentum, and energy—coupled with the thermodynamic (equation-of-state) and constitutive (stress-strain) response of the material. The computer programs developed to perform these numerical simulations are generally called *hydrocodes*, a contraction of "hydrodynamic computer codes." Early formulations did not include strength effects. Thus, metals were treated as fluids, with no viscosity, and the expression, "hydrodynamic computer code" came into use. The first applications of these computer codes in penetration mechanics were to hypervelocity impact,[1] where the impact pressures were significantly higher than the flow stress (strength) of the material, thus providing the rationale for ignoring strength effects. Later formulations included strength effects, but the term *hydrocode* has persisted.

Two fundamental descriptions of the kinematic (time-dependent) deformation of continuous media exist: the Eulerian (spatial) and Lagrangian (material) description. The partial differential equations of continuum mechanics are discretized to permit a numerical solution.[2] That is, the region of interest is divided (discretized) into a computational mesh consisting of a large number of cells, zones, or elements that map out the interaction region and the materials. The equations are computed at successive increments of time (time steps) to solve for the time-dependent motion of the interacting materials. The integration time steps are computed from the Courant stability criterion that states that the time step Δt is limited by the time a stress wave can travel across a computational zone, $\Delta t = \Delta x/c$, where Δx represents the distance across a computational cell, and c represents the wave velocity. The smallest cell in the computational mesh sets the limit on the time step.

The essential difference between the computational implementation of the two descriptions is that the computational mesh is fixed in space for the Eulerian description, and the computer program calculates the flow of mass, momentum, and energy across mesh (cell or element) boundaries; the computational mesh is attached to the material in the Lagrangian description, and the computer program calculates motion of the mesh, that is, the points (nodes) of the mesh move with the local material velocity. Generally, it is desirable to work in Lagrangian coordinates, since the time history of material deformation is calculated directly; however, the computational mesh usually becomes highly compressed and distorted in impact problems.[3]

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[1] W. E. Johnson and C. E. Anderson, Jr., "History and Application of Hydrocodes in Hypervelocity Impact," *Int'l. J. Impact Eng.*, *5*, 1–4 (1987), 423–439.

[2] C. E. Anderson, Jr., "An Overview of the Theory of Hydrocodes," *Int'l. J. Impact Eng.*, 5, 1–4 (1987) 33–59.

[3] Ibid.

Backofen and Williams,[4] as part of a larger survey focused on kinetic energy penetrator work performed by Soviet researchers, provided a review of computational penetration mechanics. At the time of their report, Backofen and Williams stated that computational penetration work appeared to be performed principally in the Moscow region, although the models were being exercised at other locations. They concluded that the principal organizations and personalities that had influenced the development of these computational models were:

- Problems of Mechanics Institute, Moscow (L. A. Chudov);
- Mechanics Scientific Research Institute, Moscow State University im. M. V. Lomonosov, Moscow (S. S. Grigoryan);
- Chair of Gas And Wave Dynamics, Moscow State University im M. V. Lomonosov, Moscow (Kh. A. Rakmatulin and A. Ya. Sagomonyan).

However, Backofen and Williams were unable to draw any conclusions or make any assessments of the Soviet state of the art in computational KE penetration analyses. Indeed, as will be seen below, only a few Soviet papers that examined the impact of projectiles against targets appeared prior to 1979, although the application of hydrocodes to shock wave physics (flyer plate impact) problems dates back to the mid-1960s.

One of the things that makes it somewhat difficult to assess the capabilities and evolution of hydrocodes in the former Soviet Union, and the distribution of a code among various Soviet research centers, is that Soviet researchers generally have not provided the names of the computer programs they have used. Information must thus be inferred from general descriptions and capabilities provided by authors. Although different computer programs certainly have grown up in the various research centers, it does appear that many of the numerical algorithms are common. In addition to Soviet publications available in translation, there have been a large number of untranslated presentations delivered at numerous Soviet conferences. We can presume that there has been a technical interchange between the various organi-

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[4] J. E. Backofen, Jr., and L. W. Williams, "Soviet Kinetic Energy Penetrators—Technology/Development," Battelle Columbus Laboratories, Columbus, Ohio, ADB035438 (1979).

zations through these conferences. An exception to this may be the occasional paper by a university professor; however, few of these exist, and some of their numerical approaches have been considerably different from those originating within one of the research sites.

C. DISCUSSION

Soviet researchers have long been interested in the viscosity of metals (Il'yushin, 1940, 1941; Popov, 1941). The interest in viscous effects has been particularly prevalent in papers examining shock wave profiles (Godunov et al., 1971; Godunov and Kozin, 1974; Godunov et al., 1975; Kozin, 1977). Shock structures have the singular attribute that, for wave velocities less than the velocity of sound, the wave profile suffers a discontinuity. Such a front structure, split into an elastic precursor (called elastic predecessor in the Soviet literature) and a plastic wave, has been observed repeatedly in experimental investigations of shocks in metals. Figure VI.1 provides an idealized (elastic, perfectly plastic) shock wave profile that shows the elastic precursor, which is traveling faster than the main shock.

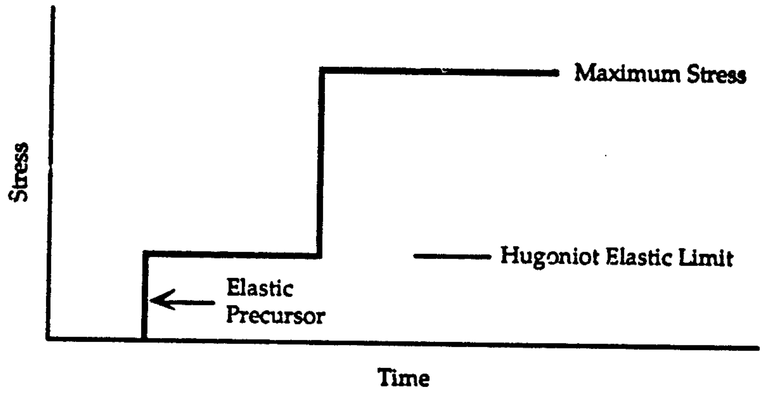

Figure VI.1
Schematic of Propagating Shock Wave with Elastic Precursor

It is known that the deformation of material depends essentially on not only the magnitude of the load acting on it, but also on the rate of its application. In the

Soviet research, materials have often been regarded as a viscoplastic body, for which the relation between the stress σ and the strain rate $\dot{\varepsilon}$ is given by

$$\sigma = \sigma_Y + \eta\dot{\varepsilon} \tag{1}$$

where σ_Y is the yield stress of the metal and η is the viscosity coefficient. Godunov et al. (1971) used explosive welding experiments to estimate the viscosity coefficient. This model of a viscoplastic solid was used during the processing of experiments to measure the coefficient of viscosity η. Further work was performed by Godunov et al. (1975) to determine the viscosity of metals from the symmetric oblique collision of plates when reverse jets exist. Soviet researchers have presented results on determining the values of η as interpolation formulas for the stress-relaxation time τ, $\eta = G\tau$, where G is the shear modulus. Certainly one driving force, and probably the primary motivation for this work, was to obtain independent measurements of the metallic viscosity for computational simulations of shock wave experiments and the desire to match shock wave profiles that exhibited elastic precursors.

From the point of view of a computational implementation, the viscosity is interpreted as leading to an overstress σ that then relaxes back, at some characteristic relaxation time, to the "quasi-static" yield surface. The time rate of change of the deviatoric stress σ^d is calculated from some instantaneous value σ^d and the equilibrium value σ^d_e by an equation that has a form represented by

$$\frac{\partial\sigma^d}{\partial t} = 2G\left(\dot{\varepsilon} - \frac{\sigma^d - \sigma^d_e}{\tau}\right) \tag{2}$$

where $\dot{\varepsilon}$ is the distortional strain rate, and τ is the relaxation time.

Godunov and Kozin (1974) indicated that the viscosity is inversely related to the shear stress relaxation time, although this must be either a mistranslation or simply an error, since a slightly later paper by Godunov et al. (1975) stated that they are proportional. This work can be compared to that of Steinberg, Breithaupt, and

Honodel,[5] who also showed that the viscosity is related to the shear stress times the relaxation time $\eta = 2G\tau$, with the only difference being in the coefficient 2.

To produce a better fit between computations and experimental shock wave profiles, Godunov and Kozin (1974) postulated a strongly varying relaxation time in terms of the temperature, compression, and shear stress. The relaxation time τ was expressed as

$$\tau = \tau_0 (\sigma/\sigma_0)^m e^{-U(\sigma,T)/RT} \tag{3}$$

where $U(\sigma, T)$ is the activation energy, R is the universal gas constant, T is the temperature, and τ_0 and σ_0 are constants. With this representation, and the extra flexibility given by the adjustable constants, they were able to demonstrate a steep (elastic) front being formed on the relaxation layer, which can be isolated in an individual wave.

Kozin (1977) carried out additional theoretical work to justify the relationship represented by Equation (3). He assumed that the dissipation mechanism was the result of viscous friction with a small viscosity coefficient. He then showed that the energy dissipation mechanics with small internal friction has the effect of smearing elastic discontinuities on the shock profiles, proportional to the viscosity coefficient, thereby justifying the relations adopted in Godunov and Kozin (1974) at those discontinuities.

To investigate strength effects, it is necessary to have good low-pressure equations of state. Thus, during this period, there was also an effort to develop an efficient computational equation of state and to define the constants for a variety of materials. A theory was developed to extend the Debye equation of state for metals to very low pressures, where strength effects are important (Godunov et al., 1974). In this generalization, an interpolation polynomial in terms of the compression was assumed for the Debye temperature. It is quite evident that the construction of interpolation formulas was for numerical applications. Subsequent research placed

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[5] D. Steinberg, D. Breithaupt, and C. Honodel, "Work-Hardening and Effective Viscosity in Solid Beryllium," X Int'l. Conf. on Research at High Pressure (AIRAPT), Amsterdam, The Netherlands, 8-11 Jul 1985.

restrictions on the interpolation formula by stating that permissible equations of state must satisfy certain inequalities (Kozin, 1976). From the interpolation formulas, the equation of state, entropy, and the stress components, along with the longitudinal and shear wave velocities, were calculated. The thermal conductivity, as a function of temperature, was also determined as an explicit expression involving the longitudinal sound velocity, the Debye temperature, and the Debye time. Kozin et al. (1978) later provided constants for 24 metals. In this work, the thermodynamic relationships in the theory of plasticity were examined. The density of the defects formed took into account the dependence of the internal energy on the elastic strain, and the entropy took account of the internal energy redistribution because of heat generation. On the basis of the equation of state constructed, the magnitude of the work in undergoing plastic deformation (and the formation of defects) was estimated. Interpolation formulas were constructed for the elastic energy to account for the increase in internal energy resulting from plastic deformation and defect formation in the crystal lattice. Kozin et al. mentioned that the specific applications were for problems with finite (large) strains.

The work described above focused primarily on the use of a one-dimensional Eulerian formulation, used in the investigation of shock profiles. However, the equation-of-state work certainly was applicable to multidimensional hydrocodes. Since the equation of state was specifically formulated for numerical applications and the constants for a large number of materials were provided, this equation-of-state formulation probably has been widely used by other Soviet researchers.

Some dissipative mechanism is required to reduce numerical oscillations that are induced by very sudden changes, such as occurs at a shock front.[6] In the United States, artificial viscosity, a purely numerical artifact, has been introduced to limit numerical oscillations, dating back to the work of von Neumann and Richtmyer.[7] In the Soviet numerical work, because a dissipation mechanism already existed—metal viscosity—at the shock front, there was no need to introduce artificial viscosity within the numerical framework. Indeed, there was absolutely no mention in the

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[6] C. E. Anderson, Jr., "An Overview of the Theory of Hydrocodes," *Int'l. J. Impact Eng.*, 5, 1–4 (1987) 33–59.

[7] J. von Neumann and R. D. Richtmyer, "A Method for the Numerical Calculation of Hydrodynamic Shocks," *J. Appl. Phys.*, *21*, 3(1950), 232–237.

Soviet literature of artificial viscosity before the mid-1970s. However, this changed dramatically in the mid-1970s, and now their hydrocode formulations use artificial viscosity to limit numerical oscillations at shock fronts. We can speculate on the origins of this change.

As already stated, the motivation for introducing viscous effects into the constitutive behavior of metals was the desire to match experimental shock wave profiles, specifically, the wave profiles that exhibited an elastic precursor. Although Soviet researchers were working with deviatoric stresses, and were computing the onset of plastic flow using a von Mises flow criterion, they had not developed a methodology for separating elastic deformation from plastic deformation. M. Wilkins at Lawrence Livermore National Laboratory in the United States developed a computational methodology in the early 1960s for decomposing the total elastic strain rate into the elastic and plastic components; this work was translated into Russian in 1967.[8] A natural consequence of the methodology developed by Wilkins is that the formation of an elastic precursor arises naturally, being formed if the shock speed is less than the elastic wave speed.

We can assume that it took a few years from the actual translation of Wilkins' work to dissemination and wide-spread adoption. In the 1970s, Wilkins traveled several times to the Soviet Union, where he was treated with a great deal of respect,[9] which also fits into this interpretation. Virtually all of the numerical papers that discuss the numerical procedures in any detail have referenced the Soviet translation of Wilkins' work. With the introduction of a computational methodology to naturally account for the elastic precursor, there was no need to invoke metal viscosity and relaxation effects; however, without a dissipation mechanism at the shock front, it was necessary to introduce an artificial viscosity. Note however, that although there was no longer a need for viscous effects to explain the elastic precursor, Soviet researchers have maintained a strong research initiative in investigating and modeling material rate effects. This is seen in the discussion that follows, as well as the chapter on material behavior.

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[8] M. L. Wilkins, "Calculation of Elastic-Plastic Flow," in *Computational Methods in Hydrodynamics* [Russian translation], Moscow: Mir, 1967, 212-263.

[9] M. L. Wilkins, private communication, 1986.

An early example of Soviet application of the elastic-plastic methodology of Wilkins was in a one-dimensional code Simonov (1974) used to investigate the impact of a flyer plate into an elastic-plastic half-space. Quadratic artificial viscosity was used everywhere in the grid, but he found that linear viscosity could only be used near the shock front, otherwise spurious results were obtained. He examined elastic unloading waves from the rear of the flyer plate, and compared the computational results to experimental data that measured the particle velocity as a function of distance traveled into the target. It is obvious that even this one-dimensional problem taxed the computational power of existing Soviet computers. Simonov described a routine written such that at periodic time intervals, the entire motion pattern was shifted backwards by a certain number of grid points (50 or 75) to keep the problem manageable on the computer (a total of 200 to 250 grid points with 3,000 to 4,000 time steps). Problem run times were 2.5 to 3 hours on a BESM-3M.

Simonov and Chekin (1975) investigated the shock wave profiles in iron at the suggestion of L. V. Al'tshuler. To obtain agreement with experimental data, they had to account for the α–ε phase change in iron. They performed parametric studies of the shear modulus, Poison's ratio, and the flow stress to match the data, and found that the yield point and shear modulus increased significantly with pressure and exceeded their values at normal pressures by several times. It is interesting that a computational study that demonstrated the importance of the α–ε phase change in iron was performed in the United States also about the same time,[10] however, this was a two-dimensional calculation. Zhukov et al. (1984) conducted further theoretical and numerical research focused on the α–ε phase transition. In this work, the α–ε phase transition was modeled by specifically formulating a kinetic equation for the transition that accounts for the rate of transformation from one phase to the other as a function of thermodynamic potential, temperature, and phase concentration. Agreement with experimental data appears to have been quite good. An interesting feature was that Zhukov and his coworkers adopted a flux-correction method to smooth the nonphysical oscillations that arose behind the shock front, instead of artificial viscosity. This procedure introduced a diffusion mass flux and modified the density when the material was in compression. This flux-correction method was probably adapted from numerical fluid dynamics, but there is no indication that the

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[10] L. D. Bertholf, L. D. Buxton, B. J. Thorne, R. K. Byers, A. L. Stevens, and S. L. Thompson, "Damage in Steel Plates from Hypervelocity Impact II," *J. Appl. Phys.*, *49*, 9(1975), 3776–3783.

methodology was adopted by other researchers for shock propagation simulations in condensed (solid) matter.

A. I. Korneyev has been a co-author of a number of works.[11] With Gridneva et al. (1977), he performed a Eulerian calculation (using artificial viscosity) where they developed a technique, using tracer particles (referred to as the method of markers by Soviet researchers), to determine the motion of moving boundaries. The tracers moved with the medium and their velocity was determined by linear interpolation with respect to velocity at the points of a Euler grid. Some of the tracer particles moved into cells that were full. Such particles were eliminated to avoid later computational difficulties. If the surface particles spread out over a large distance, new tracer particles were added. Markers were also used to fix material points that were suspect for failure. A failure model based on applied stress and time was included in the calculation. The researchers considered the failure process as it developed in time, as a kinetic process, and employed the principle of damage accumulation

$$\int_{t_0}^{t^*} \frac{dt}{\tau(\sigma_t)} = 1 \tag{4}$$

where t_0 and t^* represented the time at the onset of damage and the instant of failure, respectively. The assumption was that the material behaved in the failure process like a Voight body with a non-Newtonian viscosity. The instantaneous strength of the material was given by

$$\sigma_t = \sigma_0 + A(d\sigma_t/dt)^n \tag{5}$$

where A and n $(0 \leq n \leq 1)$ were quantities that characterize the material (for $n = 0.5$, Equation [5] follows from dislocation theory). After further derivation, and assuming that $\sigma_t \rightarrow \sigma_T$ as $\tau \rightarrow \tau_0$ with $\sigma_T \approx 0.1E$

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[11] Gridneva et al., 1977; Zhukov et al., 1984; Bulantsev et al., 1985; Yefremova et al., 1985; Belov et al., 1985, 1988b, 1990; Korneyev and Shutalev, 1986.

$$\tau = \tau_0 \left(\frac{(\sigma_t - \sigma_0)}{(\sigma_T - \sigma_0)} \right)^{(n-1)/n} \text{for } \sigma \geq \sigma_0 \qquad (6)$$

$$\tau_0 = \frac{nA^{1/n}}{2(1-n)} (\sigma_T - c_0)^{(n-1)/n}$$

which upon inserting into Equation (4) and integrating, yielded

$$\int_{t_0}^{t^*} (\sigma_t - \sigma_0)^{(1-n)/n}\, dt = \tau_0\, (\sigma_T - \sigma_0)^{(1-n)/n} \qquad (7)$$

where the failure time is given by τ_0. Integration of Equation (7) began at the instant t_0 when tensile stresses appeared in the body for a stress σ_t greater than the threshold stress σ_0. Although the Soviet authors did not reference the paper, the model looks similar to the Tuler-Butcher model.[12]

Using this model, the Soviet researchers examined the impact of nominally identical mass but various length-to-diameter (L/D) ratio glass-shaped (hollow cylindrical) projectiles striking steel targets at 3.4 km/s. Figure VI.2 depicts the results, showing various degrees of spallation damage depending on the projectile L/D. The shaded regions correspond to zones in which there is failure, while the points indicate isolated failure. The difference in damage is a direct consequence of the time it takes for attenuation of the impact shock; the wider the projectile (the lower the L/D), the less attenuation and the more damage. The authors reported that the computational size was "not less than 40 x 40 zones." The material could go beyond the limits of the Euler grid in the computational process; therefore, an algorithm was written to shift the region occupied by the projectile and target, as an "absolutely solid body," to the origin of the computational grid. Thus, we again see a direct effect of the lack of computational power.

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[12] F. R. Tuler and B. M. Butcher, "A Criterion for the Time Dependence of Dynamic Fracture," *Int'l. J. Fract. Mech.*, 4(1968), 431–437.

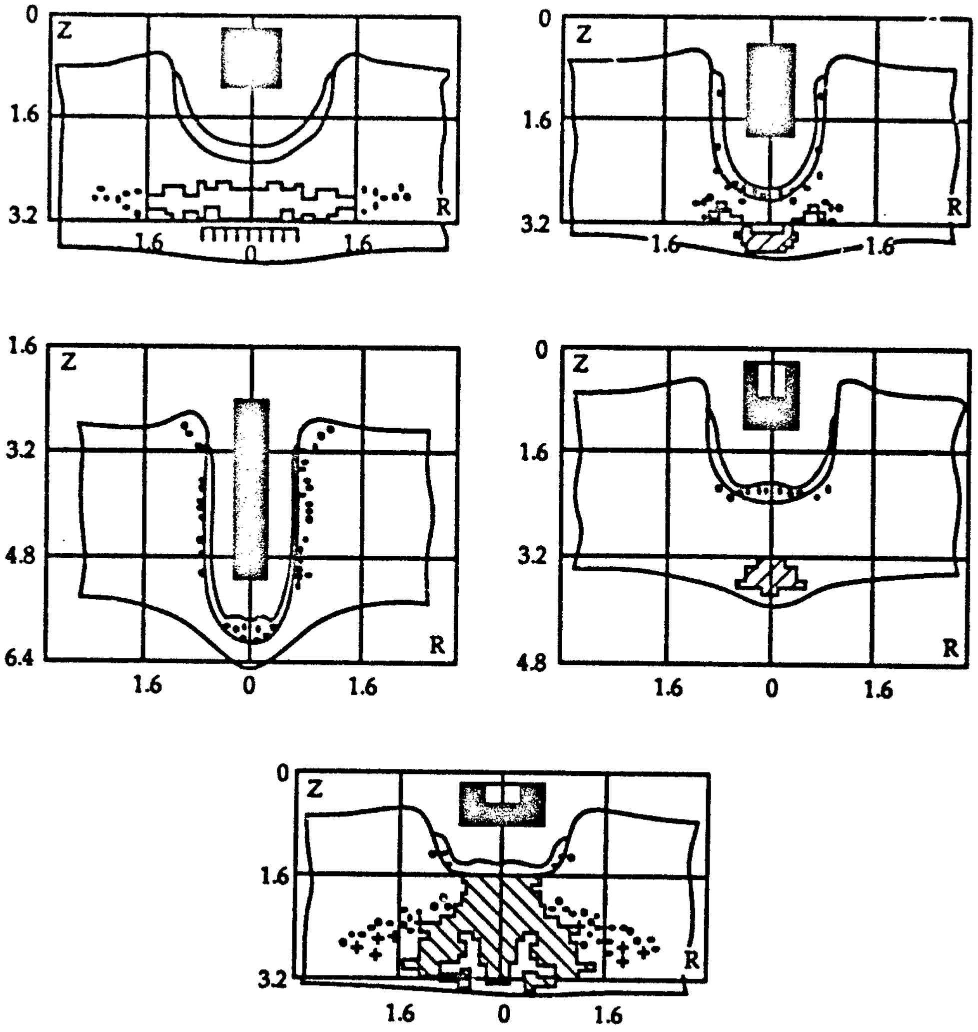

Figure VI.2
Calculations of Equal Kinetic Energy Impacts of Glass Projectiles into Steel Targets Depicting Damage Levels

Eulerian codes were almost conspicuous by their absence in the 1980s, except for use of the particle-in-cell technique, which will be discussed later. A 1979 paper by Romenskiy, who worked with Godunov, is notable because it described a three-dimensional Eulerian computer code. It used the equations of nonlinear viscoelasticity on the basis of the Maxwell relaxation model. Yefremova et al. (1985) used a Eulerian two-dimensional axisymmetric formulation (with a McCormick predictor-corrector scheme) to investigate shaped-charge collapse. Tracer particles were used to define material boundaries. In modeling the explosive detonation, they spread the detonation front over two to three cells. However, they calculated the parameters at the detonation front from the Hugoniot relations (to obtain values corresponding to the Chapman-Jouguet parameters at the detonation wave peak) using a small number of calculational points. This is contrasted with the normal method of just releasing explosive energy, which gives the correct impulse but generally does not provide the correct peak pressure. The researchers noted that they used an elastic-plastic model for the casing materials instead of treating them purely hydrodynamically, implying that this was a fairly new modeling capability; this indicates that this work occurred considerably earlier than the date of the paper.

Malama (1981) studied hypervelocity impact cratering using a Eulerian code for the early stages of impact; however, the code was modified in such a manner as to permit transition at any time from the Eulerian to the Lagrangian representation. The reason for doing this was that Malama found that the Eulerian difference scheme could not account for the correct description of a flow with phase transformations because of the intensive computational mixing of the materials. So he developed a Lagrangian variant of Godunov's Eulerian methodology. The original work (Malama, 1981) examined aluminum impacting aluminum (7 to 40 km/s). Malama used a "corrected" Tillotson equation of state. He then applied the code to tungsten impacting aluminum, a gas blob impacting aluminum, and iron impacting gabbroic anorthosite from 7 to 40 km/s (Malama, 1984). The concept of performing a Eulerian calculation for the initial stages of impact, and then mapping the results over to a Lagrangian representation, appears to have been adopted as a viable computational methodology by Soviet researchers, although the exact procedure appears to have varied between research groups. An alternate methodology will be discussed below.

Lagrangian finite-element programs dominated the research in the 1980s and early 1990s. The development of this computer program was strongly influenced by the work of G. Johnson and his EPIC code both because of the Soviet use of triangular elements and their references to Johnson's work.[13] Since Soviet researchers have tended to not mention the name of the computer program they were using, there is no way of knowing if one program emerged that was then subsequently distributed/transferred among organizations, or if there were several independent development efforts. Considering the similarities of description (and graphics) by various researchers from different organizations, it is likely the former scenario was the case, although modifications were probably made at each site. In all cases where sufficient detail on the program(s) was given, the method developed by Wilkins was used for splitting the deviatoric and spherical part of the stress tensor, and for computing the elastic and plastic components of the deviatoric stresses (using the Jaumann derivative to account for rigid-body rotation). Both linear and quadratic artificial viscosities were used to dampen numerical oscillations at the shock front.

The example represented by Figure VI.2 demonstrates one of the approaches to damage modeling, a subject that received considerable attention through the 1980s. In this respect, the Soviet work was considerably different, and more advanced, than that in the United States, where little emphasis has been placed on failure modeling in the general-purpose production codes. Because of the importance placed by Soviet researchers on failure modeling, and because of the potential usefulness of the ideas for incorporation into US hydrocodes, some of the approaches used will be summarized. All of this work unquestionably was influenced by the work at SRI

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[13] G. R. Johnson, "Analysis of Elastic-Plastic Impact Involving Severe Distortions," *J. Appl. Mech.*, 43, 3(1976), 439–444.

G. R. Johnson, "Liquid-Solid Impact Calculations with Triangular Elements," *Fluid Engng.*, 99, 3(1977), 598–600.

G. R. Johnson, "High-Velocity Impact Calculations in Three Dimensions," *J. Appl. Mech.*, 44, 1(1977b), 95–100.

International[14] and that of J. Johnson at Los Alamos National Laboratory,[15] since their work is cited quite often.

In the early 1980s, two new Soviet names arrived on the scene, V. A. Gorel'skiy and I. Ye. Khorev, evidently students of A. N. Dremin. G. I. Kanel', in his thesis work under Dremin (the thesis work is dated 1979, as indicated in Ref. 7 of the paper by Dremin et al., 1986b), developed a phenomenological failure model that has been applied to spallation, ordnance velocity impact, hypervelocity impact, and in general, the process of failure resulting from impact. The model was used extensively during the 1980s, particularly by Gorel'skiy and Khorev, Kanel', and V. Ye. Fortov, who have applied it to a wide variety of impact studies. It also appears that the model has served as a point of departure for more micromechanically based models. Succinctly, the model has the following features (Sugak et al., 1987).

The model employed is one of a medium subject to damage, characterized by the presence of microcavities (cracks, pores). The overall volume V of the medium is made up of the undamaged part, which occupies a volume V_s and is characterized by a density ρ_s, and the microcavities, which occupy volume V_C in which the density is assumed to be zero. The specific volume and the density, which is the inverse of the specific volume, are given by

$$V = V_S + V_C \tag{8}$$

$$\rho = \rho_s V_s / V . \tag{9}$$

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[14] T. W. Barbee, L. Seaman, R. Crewdson, and D. Curran, "Dynamic Fracture Criteria for Ductile and Brittle Materials," *J. Mater.*, 7, 3(1972), 393–401.

D. R. Curran, D. A. Shockey, and L. Seaman, "Dynamic Fracture Criteria for a Polycarbonate," *J. Appl. Phys.*, 44, 9(1973), 4025–4037.

L. Seaman, D. R. Curran, and D. A. Shockey, "Computational Models for Ductile and Brittle Fracture," *J. Appl. Phys.*, 47, 11(1976), 4 814–4826.

D. R. Curran, L. Seaman, and D. A. Shockey, "Dynamic Failure of Solids," *Physics Today*, 30, 1(1977), 46–55.

[15] J. N. Johnson, "Dynamic Fracture and Spallation in Ductile Solids," *J. Appl. Phys.*, 52, 4(1981), 2812–2825.

The formation of cracks and the damage to the material caused by tensile stresses are described by a continuum model. The specific volume of cracks V_c is adopted as the measure of damage. The change in V_c is described by the kinetic equation

$$\frac{\partial V_c}{\partial t} = 0 \qquad\qquad |\sigma_{max}| < \sigma_0 \frac{V_{c1}}{V_c + V_{c1}}$$

$$\frac{\partial V_c}{\partial t} = -k_c \left(\frac{\sigma_{max}}{|\sigma_{max}|}\right)\left[|\sigma_{max}| - \sigma_0 \frac{V_{c1}}{V_c + V_{c1}}\right](V_{co} + V_c) \qquad |\sigma_{max}| \geq \sigma_0 \frac{V_{c1}}{V_c + V_{c1}} \tag{10}$$

where $|\sigma_{max}|$ is the normal stress with the maximum absolute value, k_c is a quantity inversely proportional to the viscosity of the material (note that material viscosity is still intimately connected to material modeling), V_{c1} is a parameter defining the decrease of the threshold stress in damaged material ($V_{c1} \sim 0.01 V_0$, where V_0 is the specific volume of the solid material under normal conditions), V_{co} is the initial specific volume of pores, and σ_0 is a value intermediate between the value of the spallation strength and the true fracture stress in the static condition. Essentially, k_c, V_{co}, and V_{c1} are constants to be determined experimentally. Equations (10) are used to calculate both the growth and closure of discontinuities.

The reduction in shear strength and elastic properties of the material during failure, and the softening of the yield surface, are described by the relations

$$E = E_0 \frac{V_{c1}}{V_c + V_{c1}} \tag{11a}$$

$$G = G_0 \frac{V_{c1}}{V_c + V_{c1}} \tag{11b}$$

$$Y = \left\{\begin{matrix} Y_0(1 - V_c/V_{c2}) & V_c < V_{c2} \\ 0 & V_c \geq V_{c2} \end{matrix}\right\} \tag{11c}$$

where E_0, G_0, and Y_0 are the modulus of elasticity, the shear modulus, and the flow stress in the material without failure. V_{c2} is another material constant. The equation of state is often written as a polynomial in the density

$$P = \sum_{n=1}^{3} K_n\left(\frac{\rho}{\rho_0}-1\right)^n\left[1-K_0\left(\frac{\rho}{\rho_0}-1\right)/2\right] + K_0\rho_0 E \tag{12}$$

where K_0, K_n, ρ_0 are constants of the material. With V_0 and V as the initial and current specific volumes, the expression for the pressure is also modified to account for the current specific crack volume

$$P = \sum_{n=1}^{3} K_n\left(\frac{V_0}{V-V_c}-1\right)^n\left[1-K_0\left(\frac{V_0}{V-V_c}-1\right)/2\right] + K_0\rho_0 E\,. \tag{13}$$

In more recent work, Khorev et al. (1989) modified the evolutionary equation for V_c

$$\frac{\partial V_c}{\partial t} = -P\,\frac{a_1\,exp(V_c/V_{c0})\,exp(P/P_0)}{a_2 + exp(P/P_0)} \qquad V_c > 0 \text{ or } (V_c = 0 \text{ and } P < 0)$$

$$\frac{\partial V_c}{\partial t} = 0 \qquad P > 0 \text{ and } V_c = 0 \tag{14}$$

with a_1, a_2, and V_{c0} constants of the material that are determined experimentally.

The computer program of choice, although not mentioned by name, was a Lagrangian finite element program with triangular elements. Khorev, Gorel'skiy, and coworkers have done a series of Taylor anvil type problems, but at various striking obliquities to investigate and understand ricochet (Khorev et al., 1985; Gorel'skiy et al., 1985). They applied the failure model to the calculation of a traditional Taylor impact problem (normal impact) and compared the results to experiments, then performed analysis of asymmetric impacts (Dremin et al., 1986b; Gorel'skiy et al., 1986, 1987). Figure VI.3 depicts the specific crack volume (in cm^3/g) for a normal impact study (Bogomolov et al., 1986) where the results were compared with experiments. Figure VI.4 depicts the ricochet of a deformable projectile striking a rigid target at 300 m/s at an obliquity angle of 45°. As late as 1988, they were still examining oblique impacts of cylinders (L/D = 1, 2, and 3) against a rigid target as a function of striking angle (Khorev and Yugov, 1990).

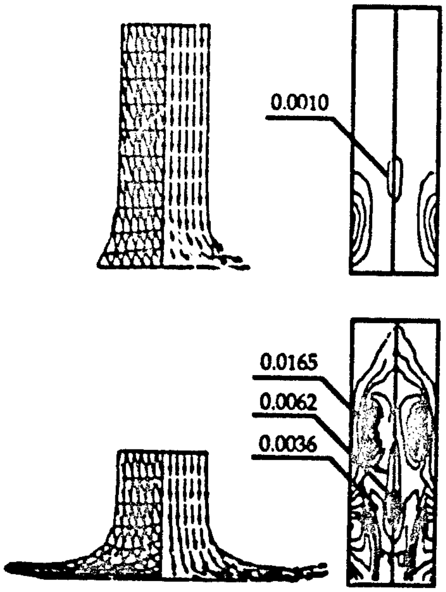


Figure VI.3
Taylor Anvil Test Depicting Specific Crack Volumes

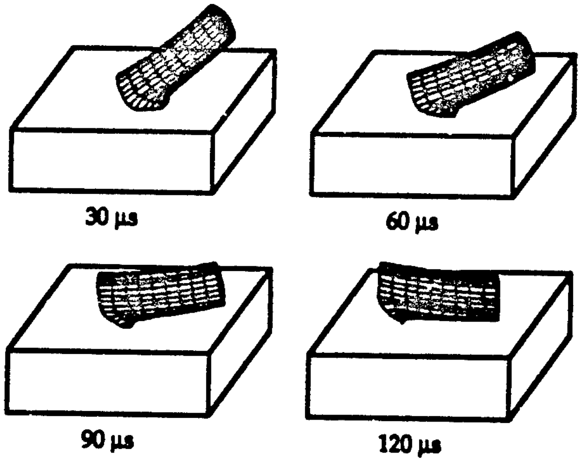


Figure VI.4
Stages of the Ricochet of a Projectile

Bulantsev et al. (1985) also studied ricochet using triangular elements and the method of Wilkins. They found that having a tensile stress, $\sigma_{nn} \geq 0$, along the entire contact surface was a necessary but not sufficient condition for separation, since the target could be moving with the impact velocity. Instead, it was necessary to examine the normal component of the momentum. They performed axisymmetric calculations and plane strain calculations, and developed a single curve $u_0 \sin \phi = u_*$ to represent the relationship between impact velocity and angle of obliquity, where the constant is determined from $\varphi = 90°$ (rebound is a limiting case of ricochet) and is equal to the impact velocity u_0 where the striker rebounds at a near zero velocity. Indentation and penetration occur for $u_0 \sin \phi > u_*$.

Bulantsev and his coworkers presented the results of experiments where steel spheres were fired at aluminum plates, and agreement between theory and experiments was quite good, as shown in Figure VI.5. The open circles represent spheres that ricocheted, and the solid circles represent spheres that penetrated into the target plate. A different (theoretical or experimental) curve is needed for each pair of materials.

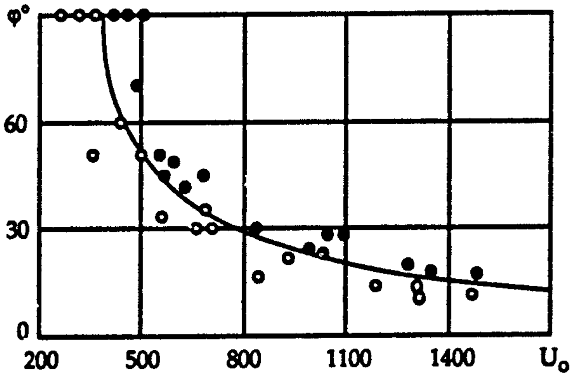


Figure VI.5
Ricochet Curve

The damage model has been applied to numerous investigations of spallation damage, most of which were not available in English translations, by Kanel', Fortov, Khorev, and Gorel'skiy. However, a few of their papers have been translated. They have investigated impact, penetration, failure, and breakout of finite-thickness plates. Examples include surface fracture of plates (Dremin et al., 1986a); kinetic mechanisms of single plate perforation (Sugak et al., 1987; Gorel'skiy et al., 1987; Gorel'skiy et al., 1988b); and two-layer, but spaced plate interactions (Gorel'skiy et al., 1988a). Khorev et al. (1989) examined multiple (synchronous) impacts. The initial deformation behavior of an oblique (15°) impact of a L/D = 3 steel projectile into a steel target at an impact velocity of approximately 1.5 km/s is depicted in Figure VI.6 (Gorel'skiy et al., 1987). The first figure shows both the projectile and the target, while the other two figures separate the projectile and target deformations. The interaction of spaced targets is depicted in Figure VI.7 (Gorel'skiy et al., 1988a). To make a detailed investigation of the mechanism of perforation of two-layer plates, the Soviet researchers developed a number of relationships characterizing the development of fracture and interactions of the plates as a function of plate separation, and the deposition of energy in a monolithic plate and two-layer plate of equivalent mass.

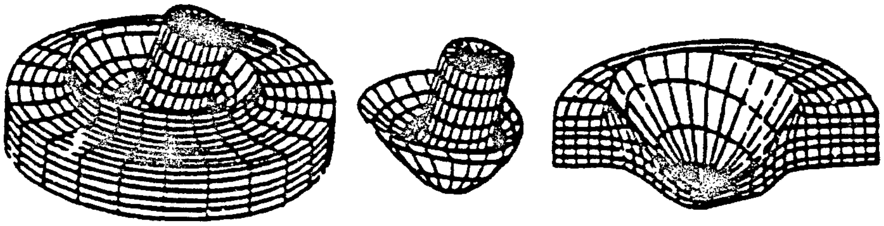


Figure VI.6
Oblique Impact of a Steel Projectile into a Steel Plate at 1.5 km/s 16 μs after Impact

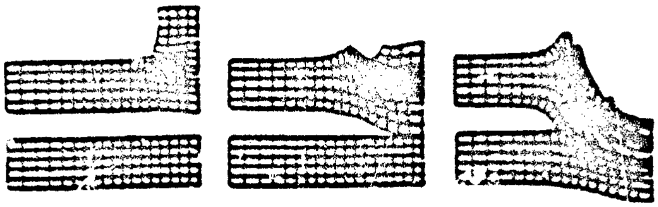
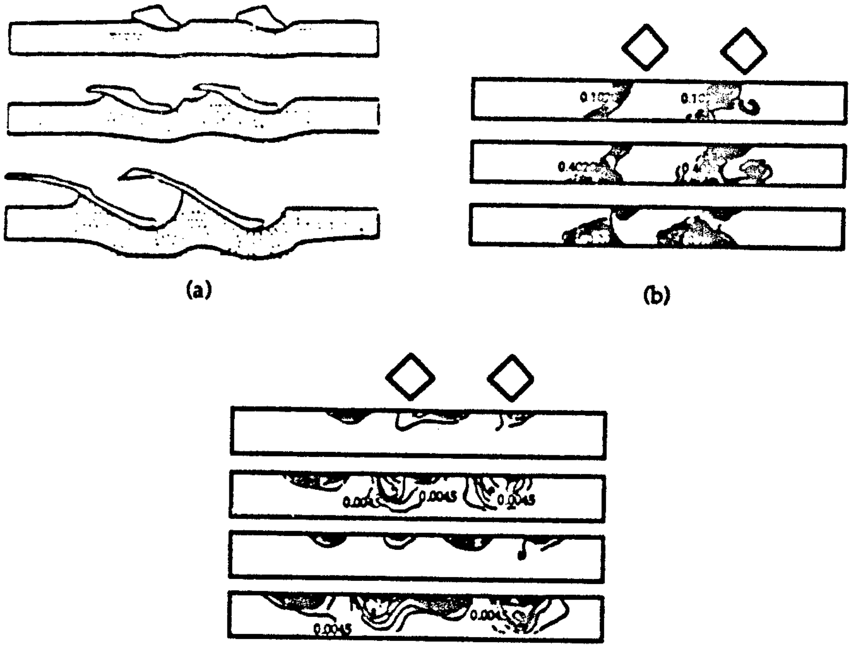


Figure VI.7
Depiction of Spaced Plate Impact Study

Figure VI.8 shows the simultaneous impact of two "chunky" steel fragments impacting a finite-thickness steel plate; these particular calculations were done in two-dimensional plane strain (Khorev et al., 1989). The particle velocity was 2.69 km/s, and the impact angle was 60°; the initial distance between the particles was varied in the parameter study. Figure VI.8a shows the deformations at 4, 8, and 16 μs after impact for an initial fragment separation of 24 mm. The failure model used in the calculations only permitted damage growth in zones of negative pressure; negative pressure contours are shown for 4.5, 5.0, and 6.0 μs after impact in Figure VI.8b. The asymmetry resulting from multiple impacts is evident. Figure VI.8c shows the distribution of isolines of the specific crack volume at 4 and 8 μs for an initial fragment separation distance of 24 mm (above) and 34 mm (below). With the larger separation distance, the damaged regions develop virtually independent of each other.

In summary, not only has the complexity of the problems examined increased with time, but some very detailed and serious studies have been performed to study the interaction of projectiles with targets. The projectile material (steel) and impact velocities, and the short L/Ds, suggest that the threats being considered are fragments from warheads, and perhaps small-caliber and medium-caliber weapons. The investigation of ricochet and multiple impacts also suggests warhead fragments. However, for some of the higher impact velocities (greater than 3 km/s), the applicability may have been focused on explosively formed projectiles (EFPs). In regard to applicability, no numerical publications have emerged that examine the impact of long-rod kinetic energy projectiles against heavy armor targets. Surely this work also was being performed.



(a)

(b)

(c)

Figure VI.8
Calculations of Simultaneous, Multiple Impact

To provide better definition of failure, Aptukov et al. (1986) performed experiments using Moiré fringes to investigate the strains on an explosively loaded aluminum plate. They modeled the detonation, and developed a model for zones of macrofractures (that is, formation of free surfaces) inside the plate using two-dimensional Lagrangian calculations (triangular elements, with slide lines).

The failure methodology has also been applied to hypervelocity impact (Anisimov et al., 1984; Agureykin et al., 1984; Inogamov et al., 1991), specifically to examine impacts from Halley's comet on the Vega spacecraft. To perform the studies, an equation of state over a broad range of parameters, including the melting curve and the two-phase region was needed. The authors reported the use of a semi-empirical, wide-range equation of state that contained about 20 adjustable parameters, determined from experiment and from quantum-mechanical calculations. The equation of state had the correct asymptotic behavior in all limiting cases (low and high densities and high temperatures). The formation of cracks and damage to the material caused by tensile stresses were described by the damage model that calculated the evolution of the specific volume of cracks, including crack-rate growth, as described in Equation (10) and following. The increase in the yield point due to strain hardening and the decrease in the yield point due to the formation of microscopic cracks were also taken into account.

What is particularly interesting in this Soviet work was the use of the particle-in-cell (PIC) Eulerian technique for the initial deformation response for calculations of hypervelocity impact. There is absolutely no chance of confusion that it is the PIC methodology that has been used. The authors reference Frank Harlow's work.[16] The calculation of the hypervelocity impact of a particle against a bumper shield configuration is one of the most taxing problems for hydrocodes.[17] The spatial scale of the problem varies with time over wide limits. The interaction of the striking particle with the bumper shield—the initial stage of impact—requires a computational mesh that is a few times the size of the particle. After interaction with the bumper plate, the spatial scale is on the order of the distance between the bumper and the main plate. For the cometary impact problem, the scale size switches from 10^{-2} cm to 10 cm between the two stages of impact. Thus, it is practically impossible to compute the entire sequence without resetting the computational mesh. Further, there is a sharp spatial nonuniformity, particularly in the initial impact stage, which favors a Eulerian methodology. However, the final stage of impact, where the details of damage on whether or not the plate can stop the debris cloud are important, favors a Lagrangian representation (the Eulerian representation, with a first-order accurate advection algorithm, leads to numerical diffusion of damage over the computational mesh).

Therefore, the initial stages of the hypervelocity impact calculation, including the transport of the debris across the void to the second target plate and initial inter-

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[16] F. H. Harlow, "Particle-in-Cell Computing Method for Fluid Dynamics," in *Computational Methods in Hydrodynamics* (Russian translation), Moscow: Mir, 1967.

[17] C. E. Anderson, Jr., T. G. Trucano, and S. A. Mullin, "Debris Cloud Dynamics" *Int'l. J. Impact Engng., 9,* 1(1990), 89-113.

action of the debris with the second target plate, were accomplished using the PIC methodology. After the pressure fell in the diverging shock wave to about 1 to 0.5 Mbar, the Soviet researchers then mapped the PIC results into a Lagrangian description. Typical grids were 70 zones by 70 zones; the impacting particle was approximately 6 x 18, 10 x 10, or 18 x 6 zones, depending upon the mass of the particle. Up to 50,000 particles were used in the PIC computations. From 1,000 to 3,000 time steps were calculated (NORD-50 computer).

One of the advantages of the PIC method is that it is easy to separate the contact boundaries between substances and track the Lagrangian particles, thus, making it relatively easy to map the material boundaries over to a Lagrangian representation. Anisimov, Inogamov, and their coworkers reported they would have liked to have performed three-dimensional calculations, but such calculations were too computer intensive. Instead, they performed plane strain calculations for high obliquity impacts. Figure VI.9 shows the results of a 10^{-7}-g particle (with an initial density of 1 g/cm^3) 310 ns after impact into a 0.5-mm thick aluminum plate at 80 km/s. The shield is near the limit thickness for this mass (and density) particle at 80 km/s. The PIC results have been mapped to the Lagrangian mesh. Phase boundaries and contour lines of constant damage (the difference in values on adjacent contour lines is 0.01 V_c) are shown in the figure.

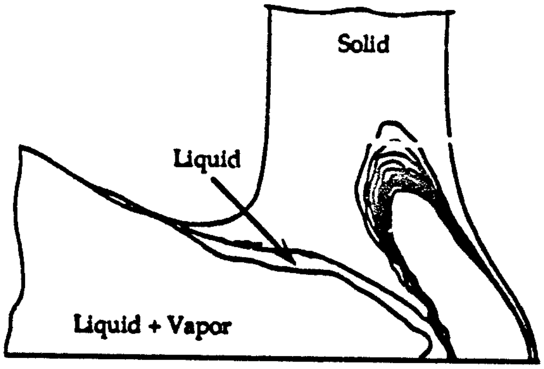

Figure VI.9
Phase Boundaries and Curves of Constant Damage for 80 km/s Impact

A number of Soviet researchers have investigated micromechanically based failure models (for example, Ruzanov, Merzhiyevskiy, and Resnyanskiy; and Kiselev). Although there have been points of commonality, the details have often differed between various investigators. Some of their modeling efforts are described below. Again, it is worth pointing out that these research efforts were significantly influenced by Curran, Shockey, and Seaman at SRI International, and J. N. Johnson at Los Alamos.

In essence, the application of the continuum model to a continuum with defects is based on the possibility of averaging the characteristics of two phases over the volume of the body. In models with internal state parameters, it is normal to suggest that failure occurs when the value of a parameter reaches a critical magnitude. A simple version of this model is obtained if it is assumed that the internal parameter only characterizes the process of continuous failure, that is, damage accumulation, and it does not affect the deformation process in the material since the internal parameter does not enter into the fundamental equations for the medium. More complex models take account of the reciprocal effect of deformation processes, damage accumulation, and temperature effects. Indeed, the model of Kanel' (Sugak et al., 1987) described earlier in this chapter represents a model where the damage parameter affects the elastic modulii, the yield surface, etc.

In general, the scope of describing failure is a two-stage process. The first stage consists of damage accumulation with plastic flow. In the second stage, failure by crack propagation occurs due to stored elastic energy. The process of damage accumulation is further subdivided into two stages.

Kiselev assumed that during the first stage there was accumulation of point defects (that is, initiation of damage); and, in the second stage, there was growth of pores that was the result of merging of point defects (Kiselev and Yumashev, 1990; Kiselev, 1991). In the second stage, pore growth was determined by the viscosity and inertial properties of the material, for example,

$$\frac{\dot{R}}{R} = \frac{\sigma_m - \sigma_0}{\eta} \qquad (15)$$

where η is a constant value with a dimension of viscosity, σ_0 is a threshold stress, and σ_m is the mean stress.

Ruzanov numerically investigated the effect of tensile stresses in the initiation and growth of voids leading to spallation (Ruzanov, 1984, 1985; Novikov and Ruzanov, 1991). He used a finite-difference scheme in Lagrangian variables with artificial viscosity. In his research, he relied heavily on work published by the SRI International group. In the model, pore volume grows with time, and depends upon the pressure

$$V_n = V_{no} e^{[3\eta(P_S - P_{go})\Delta t]} + 8\pi \dot{N} R^3 \Delta t \qquad (16a)$$

$$\dot{N} = \dot{N}_0 e^{[(P_s - P_{no})/P_l]} \qquad (16b)$$

where P_s is the pressure in the solid, R_0 is the size distribution of pores, $\dot{N}$ is the rate of pore generation per unit volume, P_{go} is a material constant, P_{no} is a threshold pressure value below which there is not pore formation, η resembles to a large degree the viscosity of the material and characterizes the resistance of the material to the growth of a micropore or microcrack, and P_l is another material constant linked with the size distribution of defects. The yield condition and the deformation rates are then modified to account for the porosity. Thus, the formation and growth of defects result in a change in mechanical properties and attendant stress relaxation.

Instead of determining the micromechanical parameters directly, Ruzanov minimized the deviation of the calculated velocity profiles $W(t)$ from the experimental profiles $U(t)$

$$S = \int_0^T [W(t) - U(t)]^2 dt \qquad (17)$$

Although the constants were not derived independently of the data (velocity of the free surface for a flyer plate experiment), the assumption was that the data contained a larger amount of information on the kinetics of the fracture process (that is, the velocity was sensitive to the kinetics). Once the constants had been determined, other aspects of the model could be investigated, for example, the volume fraction of the pores formed during fracture. The results of subsequent investigations showed that the computing time required to determine the parameters simultaneously was very long. However, Ruzanov showed that the variation in R_0 and N_0 by an order of magnitude caused no marked changes in the velocity of the free surface nor in the relative volume of the pores. Thus, the parameters selected for minimization were P_{g0}, P_{n0}, η, and P_l. Even four parameters required too much computing time, so a method of partial improvement, a generalized form of the method of coordinate descent, was used to minimize S. The vector of required parameters was divided into two groups: P_{g0} and η, and P_{n0} and P_i. The parameters of the second group were maintained constant, and the parameters of the first group were determined. Subsequently, the parameters of the first group were fixed, and the parameters of the second group were selected, and the computational process repeated.

This concept of determining micromechanical constants from macroscopic data via curve fitting, then exercising the model to explore details, has been used by a number of Soviet researchers. Thus, there has been a practical compromise between the phenomenological approach taken by Kanel', Gorel'skiy, and Khorev in modeling damage and failure, and a more basic micromechanical approach. For example, Ruzanov's damage model was based on a micromechanical model, but the model parameters were not determined independent of a macroscopic failure experiment. Generally, the parameters have been determined from flyer plate spallation experiments. But the model has then been applied to other problems, and predictions compared against experiments. This novel approach appears to have been a very cost-efficient method for determining constants so that more fundamental, as opposed to phenomenological, damage models can be used.

Merzhiyevskiy and Resnyanskiy (1984, 1985, 1986, 1987) have modeled flyer plate impact, axisymmetric projectile impact, and shaped-charge jet formation using a viscoelastic Maxwell-type constitutive expression for the material response in combination with a kinetic fracture criterion. The motivation for the initial effort was the result of experiments of an exploding charge with a small casing. In one case, a small compact body was formed, and, under similar conditions, the shell was turned inside out and broken into many small fragments. Thus, there was a need for a model to accurately reflect the behavior of materials.

The authors used a technique referred to as the "mobile grid method" for the computations based originally on work by Godunov and coworkers. No details were provided on the technique, but, from other reference sources that use the same terminology, the mobile or moving grid method has been interpreted as a coupled Eulerian and Lagrangian grid. What little can be gleaned is described several paragraphs below.

Merzhiyevskiy and Resnyanskiy combined some principles of fracture mechanics with kinetic flow theory. It was assumed that a fracture at the boundary between two cells occurs when the following semi-empirical criterion is satisfied

$$\int_{0}^{t} (\sigma - \sigma_0)^n dt \geq J_0 \qquad \sigma \geq \sigma_0 \qquad \sigma = (\sigma_1^2 + \sigma_2^2)^{1/2} \qquad \sigma_1 > 0 \qquad (18)$$

where σ_0, n, and J_0 are experimentally determined parameters. In the one-dimensional case, σ is the tensile stress. In generalizing the expression to the two-dimensional case, σ is taken as the equivalent stress defined to be the modulus of the stress vector on the area forming the face of the computational cell (σ_1 and σ_2 are the normal and tangential components of the stress vector respectively). The condition $\sigma_1 \geq 0$ means that only the tensile normal stress participates in failure. Values of the constants can be tabulated for different materials, but Merzhiyevskiy and Resnyanskiy noted that the use of the model often requires additional verification since the values of the constants may vary significantly, and unpredictably, for different grades of the same material (flyer plate spall experiments were used to calibrate the constants).

Equation (18) establishes the initiation of microcracks. Ultimate failure is a consequence of the growth and coalescence of individual microcracks to form a major crack. The further evolution of the cracks that appear is treated using fracture mechanics. The cracks grow under the Griffiths condition, which relates the minimum critical stress σ_c required to open the crack to its length l_0

$$\sigma_c = \sqrt{2\beta E / \pi l_0} \qquad (19)$$

where β is the specific energy required for the formation of unit free surface, and E is Young's modulus. The velocity of the moving crack is calculated from the relation

$$w = w_0 \left[1 - exp\left(\frac{\sigma_c - \sigma}{\sigma_c}\right)\right] \tag{20a}$$

$$w_0 = 0.38c_l \tag{20b}$$

where c_l is the longitudinal sound velocity, which provides a satisfactory description of experimental data. The last equation for the crack speed is then written in the form

$$w = w_0 \left[1 - e^{(1 - \sqrt{l/l_0})}\right] . \tag{21}$$

Recent work has replaced the semi-empirical crack initiation function with a kinetic flow theory fracture condition to establish the lifetime τ under the action of tensile stress s_{11} and temperature

$$\tau = \begin{cases} \tau_0 \, exp\left(\dfrac{U_0 - qs_{11}}{kT}\right) & \dot{\varepsilon} \le \dot{\varepsilon}_1 \\ \tau_2 \, exp\left(\dfrac{s_2}{s_{11}}\right) & \dot{\varepsilon} > \dot{\varepsilon}_1 \end{cases} \tag{22}$$

where τ_0 and U_0 are the oscillation period and sublimation energy of atoms in the lattice, q is a structure-sensitive coefficient, k is Boltzmann's constant, τ_2 and s_2 are more material constants, and T is the absolute temperature. Two different expressions had to be formulated since close to a static yield limit, the dislocation velocity is determined by thermoactivation of dislocation slipping. This is the so-called thermoactivized subbarrier slipping at which, to overcome a barrier, the dislocation "waits for" an appropriate thermofluctuation. With further increase in shear stresses, the process transforms into continuous overbarrier gliding of dislocations; this occurs for $\dot{\varepsilon}_1 \sim 10^4\ s^{-1}$.

For two-dimensional cases, Merzhiyevskiy and Resnyanskiy introduced a scalar stress state variable, the equivalent stress, instead of s_{11}. The criterion was generalized for the case of variable stress s_{11} on the basis of summing the damage such that

$$\int_{t_0}^{t^*} \frac{dt}{\tau\ (s_{11})} = 1 \tag{23}$$

where t_0 is the initial moment of the application of tensile stress. This is exactly like Equation (4). The constants were determined from one-dimensional spall experiments by iterating until agreement was obtained between the code and experimentally measured values.

Belov and Korneyev have developed a damage model based on a porous solid model (Belov et al., 1985, 1988b). They wrote the basic equations of a compressible elastoplastic medium with pores and investigated numerically the disintegration process in plates under the action of dynamic loads. They considered a porosity α

$$\alpha = \frac{V}{V_m} \tag{24}$$

where V was the volume of the material containing pores and V_m the matrix volume. The kinetic equation for pore growth, that is, the variation of α in time under the action of the applied stress, assuming that the pores remain spherical during the deformation process, was given by

$$\dot{\alpha} = \left[\frac{3n}{2\eta_0}\,(-\ \Delta P)\right]^{1/n}(\alpha-1)\left[\frac{\alpha}{1-\left(\frac{\alpha-1}{\alpha}\right)^n}\right]^{1/n} \quad \text{for } \dot{\alpha}>0,\ \Delta P<0 \tag{25a}$$

$$\dot{\alpha} = \left[\frac{3n}{2\ \eta_0}\,(\Delta P)\right]^{1/n}(\alpha-1)\left[\frac{\alpha}{1-\left(\frac{\alpha-1}{\alpha}\right)^n}\right]^{1/n} \quad \text{for } \dot{\alpha}<0,\ \Delta P>0 \tag{25b}$$

$$\Delta P = P \pm \frac{2Y}{3\alpha}\ ln\left(\frac{\alpha}{\alpha-1}\right) \tag{26}$$

where η_0, n, and Y were the constants of the materials. When α reached a critical value α_* [generally, at a relative volume of $(\alpha - 1)/ \alpha = 0.3]$, the material failed. The researchers went on to provide the relationships between the stress tensor of the matrix σ_{ij}^{m} and the porous medium σ_{ij}, the spherical and deviatoric parts of the stress tensor, the yield criterion, the equation of state of the porous solid, and the pressure increment in the porous solid due to variations in the specific volume, the specific energy and the pore volume (Belov et al., 1985). For example, the von Mises criterion was modified due to porosity: $s_{ij}s_{ij} = (Y/\alpha)^2$, where the s_{ij} were the stress deviators and Y the flow stress. This approach has been applied to explosive loading, impact damage of plates, and an examination of the failure of a rectangular striker in a Taylor anvil test (Belov et al., 1985, 1988b).

The analysis was extended to investigate the mitigation of spall damage under explosive loading and impact by using spacers of porous materials since pore collapse during loading absorbs much of the energy during collapse (Belov et al., 1988a). Thus, the model has been used to investigate pore growth due to damage, and pore collapse of porous materials. Belov et al. (1990) have also applied the methodology to include the polymorphic phase transition of steel. One of the distinct advantages of a "porosity" model is that a fairly extensive theoretical background on the effects of porosity in elasticity exists (in both Soviet and Western literature). Therefore, this theoretical foundation in elasticity provides a point of departure for non-linear material response.

The Soviet literature provided one reference to the modeling of energy release in a desensitized explosive (Utkin et al., 1989), the significance of which is that it demonstrates Soviet research activity in numerical modeling of energy release. The model used simple mixture theory (in terms of the mass fraction of the reacted material) for the internal energy and specific volume between unreacted and reacted portions of the energetic material, assuming pressure equilibrium within a computational cell. The authors adopted a kinetic relation similar to, but not as complicated as, the Lawrence Livermore nucleation and growth model

$$\frac{\partial \alpha}{\partial t} = K\alpha^{\gamma}(1 - \alpha)^{(1-\gamma)}PE_{\phi} \tag{27}$$

where α is the mass fraction of the reacted explosive, and K and γ are constants that depend on the initial porosity of the explosive, and E_ϕ is the jump in specific energy in a shock wave that has passed through a particle. The form of this equation is based on the assumption that the reaction occurs at centers and that it propagates into the bulk by laminar combustion whose velocity is proportional to the pressure. It is believed that the number of centers for a given porosity depends on the intensity of the shock wave and is formally taken into account by the factor E_ϕ. The constants K and γ are determined from the best-fit condition for all experimental data. The initial behavior of $\alpha(t)$ is estimated by integrating the equation for $K\,(1-\alpha)^{1-\gamma} P E_\phi =$ *constant;* for $\gamma < 1$; this gives $\alpha \sim t^{1/(1-\gamma)}$. Hence, it is seen that although the initial rate of the process is zero in Equation (27), it is still possible for the reaction to develop. The values of K *[kg/(s-J-Pa)]* and γ depend on the initial density

$$\gamma = 0.13\left(1 + \frac{0.2}{1.75 - \rho_0}\right) \tag{28a}$$

$$\gamma = 0.48 \times 10^{-9}\left(1 + \frac{0.08}{1.72 - \rho_0}\right). \tag{28b}$$

The calculations for the increment in α are done using an implicit scheme. Utkin et al. developed a one-dimensional hydrodynamic calculation based on the scheme by Wilkins. They modeled flyer plate experiments, but to shorten the computing time, they first determined the flow field in a stationary detonation wave that then was specified as the initial data. Note, even though the computational model was strictly one-dimensional, the concern about computer time. This further reinforces the argument that there has been a general lack of computational power in the former Soviet Union. The authors reported that their experimental data covered a wide range of pressure, and that the kinetic relation of Equation (27) gave a satisfactory description of the experimental results. The model has only two constants, defined unambiguously from experiment (the position of maximum pressure depends on the ratio of K/γ, and the total reaction time at the chemical peak depends on the product $K \sin[(1-\gamma)\pi]$). Further, the dependence of the constants on porosity was consistent with the model concepts used to formulate Equation (27).

A computational procedure, referred to as the "moving grid method," and also called the "mobile grid method" in other Soviet publications (perhaps just differences in translation), has been used in a number of publications. The exact details of the algorithm have been very sketchy, but an article by Yanenko et al. (1976) discussed the computational steps. A Eulerian and Lagrangian grid were constructed such that at $t = 0$ they coincided. The boundary between the Eulerian grid and the Lagrangian grid was not fixed, but was evaluated as part of the solution process. For each time step, the solution process was divided as follows:

- The particle-in-cell (PIC) method (along with a suitable equation of state) was used as a fluid dynamical approximation.
- The pressure field and temperature field determined the location of the boundary between the Eulerian and Lagrangian grids where the elastoplasticity subregion started. For example, in the work by Agureykin et al. (1984), after the pressure fell in the diverging shock wave to about 1 to 0.5 Mbar, the calculations were switched to the Lagrangian grid. Although not specifically mentioned, tracer particles may have been used to define the boundary between the Eulerian and Lagrangian grids (the PIC particles could act as tracer particles). The authors interpolated the computational parameters from the Eulerian to the Lagrangian grid.
- The method of Wilkins was used for the computations in the Lagrangian region.

In this manner, the region where the large deformations were on-going was treated in Eulerian coordinates using the PIC method, otherwise, a Lagrangian coordinate system was used. Evidently, this technique has become quite robust, as indicated by references either directly (Merzhiyevskiy and Resnyanskiy, 1984, 1985, 1986, 1987) or indirectly (Anisimov et al., 1984).

In September 1990, a US scientist who visited the Applied Physics Institute in Novosibirsk at the invitation of Vladimir Fortov (Director of the High Temperatures Institute in Moscow) was shown a parallel processing system for hydrodynamic problems developed by Soviet researchers. The main machine is a Soviet-produced computer (PS-2000), consisting of 128 processors in a SIMD (single instruction, multiple data) configuration. The commercially produced computer had been modified using Soviet-produced chips. The computer system had been configured so that advanced computer simulations (primarily two-dimensional) could be performed by "non-experts," that is, the interface between the programmer and the computer was very user-friendly.[18] The quoted performance had 200,000-zone problems typically running in two to three hours.

The US scientist was invited to define a problem. He chose a two-dimensional hypervelocity impact that involved a 12-km/s 2-mm aluminum sphere impacting a double bumper shield at (0.2-mm thick, separated by 5 mm), followed by an aluminum witness target. This problem stressed both the equation of state (vaporization) and numerical accuracy. The problem was defined with ~40,000 zones (0.1 mm/zone), and a complete three-phase equation of state. It took approximately 10 minutes to set up the problem. It took 12 minutes to run on the PS-2000. The output results were displayed graphically in color on an animation system that provided quantitative information of the complete dynamic response. Figure VI.10 is a black and white photocopy of a color picture from the calculation. The US scientist reported,

> The calculation was impressive in that it illustrated a degree of sophistication that we had not expected—a user-friendly computer tool for engineering analysis of dynamic problems.

Upon his return to the United States, the US scientist had the same problem run on a Cray Y-MP using one processor, employing the Eulerian hydrocode CTH. The problem was run with and without vectorization; the first case took four minutes, the solution for the second case took 14 minutes.

In August 1991, V. Fortov told a US scientist (at a meeting in Japan)[19] that the PS-2000 has been expanded to 256 processors, and that they were running three-dimensional problems. A recently published report summarizes parallel processing

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[18] J. R. Asay, Trip Report on Travel–September 1990, Sandia National Laboratories (SNL), 1990; J. R. Asay, memo to E. H. Barsis, "Parallel Computing in the Soviet Union," 25 Sept 1990, SNL, 1990.

[19] J. Michael McGlaun, private conversation.

research in the former Soviet Union, and provides considerably more information than can be given here.[20]

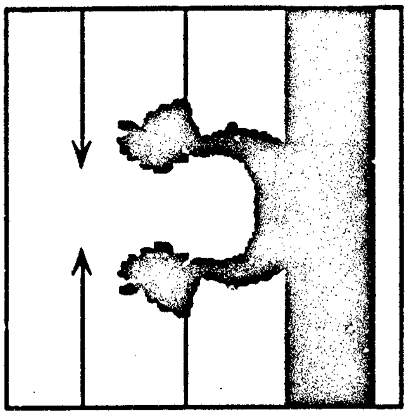

Figure VI.10
Calculation of the Hypervelocity Impact of an Aluminum Particle Against a Double Bumper Shield Using Parallel Computer Technology

The PIC method lends itself very naturally to massively parallel machines, where each processor calculates the movement of a small number of particles. Thus, we can speculate that the use of PIC for the early-time response of hypervelocity impact and the demonstration of hydrocode parallel computing go hand-in-hand. This interpretation is consistent with the moving grid algorithm described above, the work by Agureykin et al. (1984) and Anisimov et al. (1984), the hypervelocity impact demonstration problem described by Asay, and the time between the introduction of the algorithm and a "user-friendly" configured system.

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[20] J. J. Dongarra, L. Snyder, and P. Wolcott, *Parallel Processing Research in the Former Soviet Union,* FASAC Technical Assessment Report, Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, March 1992.

D. PROJECTIONS FOR THE FUTURE

In general, the lack of raw computational power in the former Soviet Union probably has prevented detailed design analysis. Some parametric studies have been performed, however, both in two dimensions and three dimensions. And these studies have certainly led to increased understanding to assist in design optimization. The design studies that have been performed appear to support light-armor design, where the threat is small- and medium-caliber weapons, and artillery fragments. No studies have appeared in the Soviet literature that demonstrate a capability of modeling long-rod penetration against such targets as semi-infinite armor steel, or elements of a heavy armor. Surely such studies have been on-going. Some of these studies may begin to appear in the literature now that the world situation has changed.

Soviet computational studies to support the Vega experiment (of which only a small fraction have been reported) are quite impressive. Soviet demonstration of massive parallel computing of hydrodynamic impact problems is equally impressive. Research will surely continue in parallel computing (hardware, programming, algorithms), although hardware is very much a limitation.[21] A distinction must be made, however, between adapting PIC and Eulerian hydrocode formulations to a SIMD machine, and adapting general-purpose finite element programs that might have a variety of elements.

It is tempting to speculate that the breakup of the Soviet Union, the rivalry between neighboring states and countries, and an emphasis on the use of conventional weaponry (as opposed to nuclear weapons) might result in an increase in computational activity. Because of the expense of production, more emphasis could be placed on computational analysis. However, computer hardware requires resources, as do the development and implementation of algorithms and programs on new machines. It is not clear that the resources will be available for such an effort. Offsetting such a development effort is the potential that the restrictions on the selling of computer hardware by Western nations might be eased. Regardless, computational power available to researchers in the successor states can only increase with time. Although the PIC methodology is well suited to massively parallel machines, a

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[21] Ibid.

stronger interest will probably arise in conventional Eulerian formulations, motivated by an interest in increased accuracy, and as researchers in the former Soviet Union read about the advances in the United States in Eulerian techniques.

One item of considerable promise is the coupling of Eulerian to Lagrangian codes to analyze the resulting structure response after impact loading. Recent Soviet ability to perform this mapping (the mobile grid methodology) provides researchers in the successor states (principally, Russia) with a strong first step in this direction. Also, since the subsequent structure response can often lead to further failure (propagation of cracks, structural softening due to damage), recent Soviet work in material failure models suitable for numerical implementation also provides Russian researchers with a strong technical background for future applications. There has long been a need in the United States for this capability, and to date, this has only been met with limited success.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table VI.1 lists key research personnel and facilities in the former Soviet Union working in numerical simulations of penetration physics.

Table VI.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— NUMERICAL SIMULATIONS OF PENETRATION PHYSICS

Applied Mathematics & Mechanics Institute,
Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)

N. N. Belov	Pore collapse, porosity, mitigation of damage, Lagrangian code, failure modeling, fracture of solids, rectangular Taylor anvil
A. N. Bogomolov	Taylor anvil, damage modeling, Lagrangian finite element
G. M. Bulantsev	Ricochet, finite element
A. N. Dremin	Oblique impact, Taylor anvil, early time response, Lagrangian finite element
G. N. Fonderkina	
V. A. Gorel'skiy	Oblique impact (low-speed, plane strain), Taylor anvil, early time response, damage modeling, 3-D Lagrangian code, multiple plate impact, ricochet, impact modeling, plugging, spallation
V. A. Gridneva	Pore collapse, mitigation of damage, Lagrangian code
I. Ye. Khorev	Oblique impact (low-speed, plane strain), Taylor anvil test, early time response, damage modeling, 3-D Lagrangian finite element, multiple plate impact, impact modeling, plugging, spallation
A. I. Korneyev	Phase transitions, McCormick two-step difference method, flux correction (smooth oscillations), explosive loading, shaped charge, ricochet, finite element, failure modeling, porosity, Lagrangian code, fracture of solids, rectangular Taylor anvil
I. I. Korneyeva	Pore collapse, mitigation of damage, Lagrangian code
P. V. Makarov	
A. P. Nikolayev	Ricochet, finite element, failure modeling, porosity, Lagrangian code
T. M. Platova	
A. V. Radchenko	Multiple plate impact, damage modeling, Lagrangian finite element, impact modeling, plugging
V. B. Shutalev	Fracture of solids, rectangular Taylor anvil, Lagrangian code
V. G. Simonenko	Phase transitions, two-step difference method, flux correction (smooth oscillations), pore collapse, mitigation of damage, Lagrangian code
Ye. G. Skorospelova	
V. A. Skripnyak	
V. F. Tolkachev	Impact modeling, plugging, damage modeling, Lagrangian finite element

Table VI.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

Applied Mathematics & Mechanics Institute, Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)—cont'd.	
V. G. Trushkov	Explosive loading, shaped charge, McCormick two-step, Eulerian difference
L. V. Yefremova	Explosive loading, shaped charge, McCormick two-step, Eulerian difference
N. T. Yugov	Oblique impact (low-speed), Taylor anvil, early time response, damage modeling, 3-D Lagrangian finite element, ricochet
S. A. Zelepugin	Multiple impact, damage modeling, Lagrangian finite element, oblique (plane strain), Taylor anvil test
T. V. Zhukova	
A. V. Zhukov	Phase transitions, two-step difference method, flux correction (smooth oscillations)
Chemical Physics Institute, USSR/Russian Academy of Sciences, Chernogolovka (Russia)	
A. N. Dremin	Impact modeling, front surface scabbing, spallation, damage modeling, Lagrangian finite element, oblique impact, Taylor anvil
V. Ye. Fortov	Shock-induced detonation, 1-D Lagrangian, impact modeling, plugging, damage modeling, Lagrangian finite element
V. A. Gorel'skiy	Impact modeling, front surface scabbing, spallation, damage modeling, Lagrangian finite element, oblique impact, Taylor anvil
G. I. Kanel'	Shock-induced detonation, 1-D Lagrangian, impact modeling, plugging, damage modeling, Lagrangian finite element
I. Ye. Khorev	Impact modeling, front surface scabbing, spallation, damage modeling, Lagrangian finite element, oblique impact, Taylor anvil
S. G. Sugak	Impact modeling, plugging, damage modeling, Lagrangian finite element
V. F. Tolkachev	Impact modeling, front surface scabbing, spallation, damage modeling, Lagrangian finite element
A. V. Utkin	Shock-induced detonation, 1-D Lagrangian
N. T. Yugov	Oblique impact, Taylor anvil, Lagrangian finite element

Table VI.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—
NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

Continuum Mechanics Institute, USSR/Russian Academy of Sciences, Perm' (Russia)

V. N. Aptukov	Moiré fringe, numerical simulations, w/damage
A. V. Fonarev	Moiré fringe, numerical simulations, w/damage
V. F. Kashirin	Moiré fringe, numerical simulations, w/damage
R. T. Murzakayev	Moiré fringe, numerical simulations, w/damage
A. A. Pozdeyev	Moiré fringe, numerical simulations, w/damage
B. I. Usachev	Moiré fringe, numerical simulations, w/damage

Experimental Physics All-Union Scientific Research Institute, Arzamas-16/Sarov (Russia)

S. M. Bakhrakh	Underground explosions, explosive channel collapse, Lagrangian with rezoning, Eulerian with turbulence effects
V. N. Mokhov	Underground explosions, explosive channel collapse, Lagrangian with rezoning, underground explosions, Eulerian with turbulence effects
A. V. Pevnitskiy	Underground explosions, explosive channel collapse, Lagrangian with rezoning, Eulerian with turbulence effects
V. A. Sarayev	Underground explosions, explosive channel collapse, Lagrangian with rezoning
V. P. Sevast'yanov	Underground explosions, explosive channel collapse, Lagrangian with rezoning, Eulerian with turbulence effects

High Temperatures Institute, USSR/Russian Academy of Sciences, Moscow (Russia)

V. Ye. Fortov	Spallation, laser pulses, numerical determination of spall strength
V V. Kostin	Spallation, laser pulses, numerical determination of spall strength

Krasnoyarsk State University, Krasnoyarsk (Russia)

N. N. Kholin	Plasticity, defect mechanics
N. S. Kozin	Numerical equation of state, shock profiles, viscosity, plasticity, defect mechanics

Table VI.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

Mathematics Institute, Siberian Branch,
USSR/Russian Academy of Sciences, Novosibirsk (Russia)

N. S. Astapov	Rock breakup, Godunov method for discontinuous solutions
A. A. Deribas	Shaped-charge jets, metal viscosity
S. K. Godunov	Shaped-charge jets, metal viscosity, shock structure, plasticity, plastic waves, numerical equation of state
V. M. Kornev	Rock breakup, Godunov method for discontinuous solutions
N. S. Kozin	Shock structure, viscosity, plasticity, plastic waves, numerical equation of state
V. I. Mali	Shaped-charge jets, metal viscosity
Ye. I. Romenskiy	Numerical equation of state, shock structure, plasticity, 3-D Euler formulation
L. D. Zakharenko	Viscosity of metals

Mechanics Scientific Research Institute, Gor'kiy/Nizhniy Novgorod (Russia)

S. S. Grigoryan	
S. A. Novikov	Damage modeling, spallation, pore volume
A. I. Ruzanov	Damage modeling, pore volume, Lagrangian finite difference, spallation, pore volume, flyer plate impact

Moscow State University im. M. V. Lomonosov, Moscow (Russia)

Kh. A. Rakmatulin	
A. Ya. Sagomonyan	
M. V. Yumashev	Failure modeling, damage parameter, spallation

Moscow State Technical University im. N. Ye. Bauman, Moscow (Russia)

L. A. Chudov	Numerical simulation, impact, penetration, interacting air shocks, Eulerian
G. P. Men'shikov	Numerical simulation, impact, penetration
V. A. Odintsov	Numerical simulation, impact, penetration
V. A. Petushkov	Numerical hydrodynamics

Table VI.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

Problems of Mechanics Institute, USSR/Russian Academy of Sciences, Moscow (Russia)	
B. S. Cheklin (Moscow)	Shock unloading profiles, phase transformation, Eulerian
L. A. Chudov	Numerical simulation, impact, penetration, interacting air shocks, Eulerian
I. V. Simonov (Moscow)	Shock unloading profiles, Eulerian (1-D), phase transformation
Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)— facilitiy not identified	
V. M. Fomin	Numerical methods, moving grids, particle in cell, Lagrangian boundary
S. P. Kiselev	Failure modeling, high-rate loading, viscosity
Ye. A. Kroshko	Numerical methods, moving grids, particle in cell, Lagrangian boundary
V. I. Liseykin	Numerical methods, moving grids, particle in cell, Lagrangian boundary
L. A. Merzhiyevskiy	Failure modeling, shaped-charge jet formation, mobile grid, shock profiles, rate effects, 1-D Lagrangian, failure modeling, penetration and perforation, dislocation dynamics
A. D. Resnyanskiy	Failure modeling, shaped-charge jet formation, mobile grid, shock profiles, rate effects, 1-D Lagrangian, failure modeling, penetration and perforation
V. P. Shapeyev	Numerical methods, moving grids, particle in cell, Lagrangian boundary
Yu. A. Shitov	Numerical methods, moving grids, particle in cell, Lagrangian boundary
V. M. Titov	Shaped-charge jet modeling, failure modeling
N. N. Yanenko	Numerical methods, moving grids, particle in cell, Lagrangian boundary
Space Research Institute, USSR/Russian Academy of Sciences, Moscow (Russia)	
Yu. G. Malama	Hypervelocity impact, cratering, Lagrangian variant of Godunov's method
R. Z. Sagdeyev	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Lagrangian code

Table VI.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

Strength Problems Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)	
Sh. U. Galiyev	Failure modeling, void nucleation and growth
S. V. Zhurakhovskiy	Failure modeling, void nucleation and growth
Theoretical Physics Institute im. L. D. Landau, USSR/Russian Academy of Sciences, Chernogolovka (Russia)	
S. I. Anisimov	Hypervelocity impact, plasma flare, particle-in-cell/ Lagrangian code, phase changes, damage modeling, space physics
A. V. Bushman	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Langrangian code
V. Ye. Fortov	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Lagrangian code
N. A. Inogamov	Hypervelocity impact, plasma flare, particle-in-cell
G. I. Kanel'	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Langrangian code
A. B. Konstantinov	Hypervelocity impact, plasma flare, particle-in-cell/ Lagrangian code, phase changes, damage modeling, space physics
R. Z. Sagdeyev	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Lagrangian code
S. G. Sugak	Hypervelocity impact, phase changes, damage modeling, space physics, particle-in-cell/Lagrangian code
S. B. Zhitenev	Hypervelocity impact, plasma flare, particle-in-cell
	Affiliation Not Identified
V. A. Andrushchenko	Interacting air shocks, Eulerian
V. A. Gridneva	Failure modeling, spall damage, 2-D effects, Eulerian
L. Ya. Ignatova	Underground explosions, explosive channel collapse, Lagrangian with rezoning
Kh. S. Kestenboym	Shock reflections, air shocks, Eulerian
A. B. Kiselev (Moscow)	Failure modeling, damage parameter, spallation
B. A. Klopov	Underground explosions, explosive channel collapse, Lagrangian with rezoning

Table VI.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—NUMERICAL SIMULATIONS OF PENETRATION PHYSICS (cont'd.)

	Affiliation Not Identified
A. I. Korneyev (Kiev)	Failure modeling, spall damage, 2-D effects, Eulerian, rigid-body impact, rod failure, Lagrangian code
E. E. Meshkov	Underground explosions, explosive channel collapse, Lagrangian with rezoning
A. I. Shurinov	Shock reflections, air shocks, Eulerian
V. B. Shutalev (Kiev)	Rigid-body impact, rod failure, Lagrangian code
V. I. Tarasov	Underground explosions, explosive channel collapse, Lagrangian with rezoning, Eulerian with turbulence effects
V. G. Trushkov	Failure modeling, spall damage, 2-D effects, Eulerian
A. A. Tuzovskiy	Plasticity, defect mechanics
S. Yu. Yefimov	Interacting air shocks, Eulerian

CHAPTER VI: NUMERICAL SIMULATIONS OF PENETRATION PHYSICS
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APPENDIX A
ABOUT THE AUTHORS

William M. Isbell *(Panel Chairman)*. Mr. Isbell is Principal Scientist of the Kinetic Energy Weapons Group at General Research Corporation. He received a BA in physics from the University of California, Berkeley, in 1957. He has been involved in hypervelocity impact research since the mid-1960s, pioneering the use of light gas guns for measurement of shockwaves in the multi-megabar regime and developing innovative instrumentation for measuring the dynamic response of materials to impact loading. His primary current activity is determining the lethality of kinetic energy weapons, ranging from long-rod penetrators to space-based interceptors. He is past founding President of the Electric Launcher Association; a past officer of the Aeroballistic Range Association; a member of the Founding Board of Directors of the Hypervelocity Impact Society; a Senior Institute Fellow of the Institute for Advanced Technology of the University of Texas; and President of ATA Associates, a manufacturer of advanced instrumentation for shockwave diagnostics. He has published over 100 reports, presentations, and papers in a wide variety of impact-related fields.

Charles E. Anderson, Jr. Dr. Anderson is Manager of the Ballistic Sciences Section at Southwest Research Institute (SWRI). He received a BS in physics from the Virginia Polytechnic Institute in 1968, and an MS and PhD in physics from the Rensselaer Polytechnic Institute in 1972. He is recognized internationally for his contributions in penetration mechanics, computational mechanics, and the use of hydrocodes to model nonlinear, high strain rate, large strain material response. He has been a member of several DOD/DOE/DARPA advisory panels to assess the status and development of material modeling and computational capabilities in the United States. Active areas of research have included modification and improvement of the predictive capabilities of the large Eulerian and Lagrangian hydrocodes, using them for warhead fragmentation effects, warhead concept development, penetration mechanics, hypervelocity impact modeling and analysis, blast loading analysis, and armor/anti-armor analysis. In particular, one focus of Dr. Anderson's work has been in the implementation of computational constitutive models to improve both the mechanics and accuracy of calculations. Such work includes the inclusion of internal state variables into Eulerian codes for constitutive modeling, the basic thermodynamics and mechanics for modeling composites within a hydrocode framework, and assisting in the development of a computational constitutive model for ceramics. Dr. Anderson is listed in *American Men and Women in Science*, and *Who's Who in the American Southwest*. He is a member of the Editorial Advisory Board for the *International Journal of Impact Engineering*, is President of the Hypervelocity Impact Society, and is a Senior Institute Fellow of the Institute for Advanced Technology.

James R. Asay. Dr. Asay is Manager of the Computational Mechanics and Adaptive Structures Department at Sandia National Laboratories. He received a BS in physics from San Jose State University in 1964, an MS in physics from the University of New Mexico in 1968, and a PhD in physics from Washington State University in 1971. He has been involved with the development and application of advanced experimental and computational techniques for hypervelocity impact research. His specific interest has focused on the role of material properties and high-rate processes on dynamic problems. He is past Chairman of the Aeroballistic Range Association, past Chairman of the Topical Group on Shock Compression of Condensed Materials, present member of the Board of Directors for the Hypervelocity Impact Society, Secretary/Treasurer of the Hypervelocity Impact Society, and is a Senior Institute Fellow of the Institute for Advanced Technology. He has published more than 100 papers in the area of dynamic material response and hypervelocity impact research.

Stephan J. Bless. Dr. Bless is Technical Director for Impact and Penetration Physics at the Institute for Advanced Technology. He received an SB in Physics (1965), an SM in geophysics (1968), and ScD in earth and planetary sciences (1970) from the Massachusetts Institute of Technology. He worked as a postdoctoral fellow at the California Institute of Technology. In 1976, Dr. Bless joined the Impact Physics Laboratory at the University of Dayton, where he became Chief Scientist. In 1991, he joined the Institute for Advanced Technology in Austin, Texas. Dr. Bless has published extensively on response of materials to dynamic loading, penetration mechanics, and armor design.

Dennis E. Grady. Dr. Grady is a Distinguished Member of Technical Staff in the Experimental Impact Physics Department at Sandia National Laboratories. He received a BS in physics and mathematics from Lewis and Clark College in 1967, and a PhD in Physics from Washington State University in 1971. He has been involved with the experimental measurement and theoretical description of condensed matter under the extreme pressure and temperature stimulus of shock and high-velocity impact. He has published over 200 technical reports and papers on a range of materials issues in the intense shock environment, including electric and magnetic effects, phase transformation, high-pressure equation of state, transient strength, and dynamic fragmentation. He is a Fellow of the American Physical Society and is currently the Vice Chair of the Topical Group on Shock Compression in Condensed Matter. He has also served in various official capacities for the Hyper-Velocity Impact Society and the International DYMAT Association.

Joseph Sternberg. Dr. Sternberg is a Professor at the Naval Postgraduate School. He received a BS in engineering (1942) and an MS in aeronautics (1943) from the California Institute of Technology, and a PhD in aeronautics (1955) from The Johns Hopkins University. His recent interests have been the behavior of ceramic materials in hypervelocity impact and the phenomena associated with unconventional hypervelocity penetrators. Dr. Sternberg is a past member of the Army Science Board. He has also served on the National Academy of Sciences Board on Army Science and Technology and is Chairman of the Lethal Systems Panel for the Academy of Sciences' study of Strategic Technologies for the Army of the 21st Century.

APPENDIX B

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

AC	alternating current
Al_2O_3	aluminum oxide
AN	*Akademiya nauk* (Academy of Sciences)
A-U	All-Union
AVS	atom-vacancy state
B_4C	boron carbide
BN	boron nitride
C	celsius (centigrade)
cm	centimeter
DC	direct current
DOP	depth of penetration
EFP	explosively formed projectile
EM	electromagnetic
EOS	equation of state
EPR	electron paramagnetic resonance
GPa	gigapascal
HE	high explosive
HEL	Hugoniot elastic limit
HfO_2	hafnium dioxide
K	(degrees) Kelvin
kA	kiloamp(ere)
kbar	kilobar
KE	kinetic energy
km/s	kilometers/second
KPT	kinetic phase transformation
L/D	length to diameter

Mbar	megabar
MHD	magnetohydrodynamics
mm	millimeter
m/s	meters/second
NAG	nucleation and growth
ns	nanosecond
ORVIS	optical recording velocity interferometer system
PIC	particle in cell
PMMA	polymethylmethacrylate
SBER	structural bond energy release
SDI	Strategic Defense Initiative (United States)
SiC	silicon carbide
SIMD	single instruction, multiple data
SiO_2	silicon dioxide
SnS	tin sulfide
SPT	scaled phase transition
SSSR	*Soyuz sovetskikh sotsialisticheskikh respublik* (Union of Soviet Socialist Republics)
TiC	titanium carbide
V	volt
VISAR	velocity interferometer system for any reflector
ZrO_2	zirconium dioxide

APPENDIX C
SOVIET JOURNALS CITED IN TEXT/REFERENCES

For readers not familiar with the technical literature of the former Soviet Union, a key to the abbreviated titles of the Soviet serial literature cited in this report is provided below. The titles of the English language translations used are listed in bold print and the original Russian-language titles are in *italics*. When a given technical journal is published in more than one commercial translation, the English title for the same Russian-language source may vary with the publisher. If translations have been made privately (for example, government agency translations), the titles may also vary. Frequently, English titles are not literal translations of the original Russian. Therefore, knowledge of the Russian title of a journal may be necessary to identify reference materials.

Abbreviation	**English Translation Title**/*Original Russian Title*
Appl. Math. Mech.	**Applied Mathematics & Mechanics** *(Prikladnaya matematika i mekhanika)*
Combust. Explo. Shock Waves	**Combustion, Explosion & Shock Waves** *(Fizika goreniya i vzryva)*
Cosmic Res.	**Cosmic Research** *(Kosmicheskiye issledovaniya)*
Dokl. AN SSSR	*Doklady Akademii nauk SSSR* (reports of the USSR Academy of Sciences—translated selectively in a number of translation publications, for example, **Soviet Physics-Doklady** or **Soviet Mathematics-Doklady**, but not translated cover-to-cover in a single publication)
Electr. Technol. USSR	**Electric Technology USSR** *(Elektrichestvo)*
Fluid Dyn.	**Fluid Dynamics** *(Izvestiya AN SSSR, Mekhanika zhidkostey i gaza)*
High Temp.	**High Temperature** *(Teplofizika vysokikh temperatur)*
Indust. Lab.	**Industrial Laboratory** *(Zavodskaya laboratoriya)*
Inorg. Mater.	**Inorganic Materials** *(Izvestiya AN SSSR, Neorganicheskiye materialy)*
	Izvestiya, Earth Physics *(Izvestiya AN SSSR, Fizika zemli)*
J. Appl. Mech. Tech. Phys.	**Journal of Applied Mechanics & Technical Physics** *(Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki)*

JETP Lett.	**JETP Letters** *(Pis'ma zhurnal eksperimental'noy i teoreticheskoy fiziki)*
	Magnetohydrodynamics *(Magnitnaya gidrodinamika)*
Mech. Compos. Mater.	**Mechanics of Composite Materials** *(Mekhanika kompozitnykh materialov)*
Mech. Solids	**Mechanics of Solids** *(Izvestiya AN SSSR, Mekhanika tverdogo tela)*
Phys. Met. Metall.	**Physics of Metals & Metallography** *(Fizika metallov i metallovedeniye)*
PMM USSR	**Applied Mathematics & Mechanics** *(Prikladnaya matematika i mekhanika)*
Russ. J. Phys. Chem.	**Russian Journal of Physical Chemistry** *(Zhurnal fizicheskoy khimii)*
Russ. Math. Sur.	**Russian Mathematical Surveys** *(Uspekhi matematicheskikh nauk)*
Russ. Metall.	**Russian Metallurgy** *(Izvestiya AN SSSR, Metally)*
Sov. Appl. Mech.	**Soviet Applied Mechanics** *(Prikladnaya mekhanika)*
Sov. J. Plasma Phys.	**Soviet Journal of Plasma Physics** *(Fizika plazmy)*
Sov. Mat. Sci.	**Soviet Materials Sciences** *(Fiziko-khimiocheskaya mekhanika materialov)*
Sov. Min. Sci.	**Soviet Mining Science** *(Fiziko-tekhnicheskiye problemy razrabotki poleznykh iskopayemykh)*
Sov. Phys.-Dokl..	**Soviet Physics-Doklady** *(Doklady AN SSSR)*
Sov. Phys. J.	**Soviet Physics Journal** *(Izvestiya Vysshikh uchebnykh zavedeniy [VUZ], Fizika)*
Sov. Phys.-JETP	**Soviet Physics-JETP** *(Zhurnal eksperimental'noy i teoreticheskoy fiziki)*
Sov. Phys.-Solid State	**Soviet Physics-Solid State** *(Fizika tverdogo tela)*

Sov. Phys.-Tech. Phys.	**Soviet Physics-Technical Physics** *(Zhurnal tekhnicheskoy fiziki)*
Sov. Phys.-Usp.	**Soviet Physics-Uspekhi** *(Uspekhi fizicheskikh nauk)*
Sov. Powder Metall. Metal Ceram.	**Soviet Powder Metallurgy & Metal Ceramics** *(Poroshkovaya metallurgiya)*
Sov. Tech. Phys. Lett.	**Soviet Technical Physics Letters** *(Pis'ma v zhurnal tekhnicheskoy fiziki)*
Strength Mater.	**Strength of Materials** *(Problemy prochnosti)*

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APPENDIX D

SOVIET RESEARCH FACILITIES CITED IN TEXT

(* full information not available)

Applied Mathematics & Mechanics Institute, at Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)
(Institut prikladnoy matematiki i mekhaniki—IPMiM/Tomskiy gosudarstvennyy universitet imeni V. V. Kuybysheva)

Applied Physics Institute, Novosibirsk (Russia)
(Institut prikladnoy fiziki)

Applied Physics Problems Scientific Research Institute im. A. N. Shevchenko, at Belorussian State University im. V. I. Lenin, Minsk (Belarus)
(Nauchno-issledovatel'skiy institut prikladnykh fizicheskikh problem im. A. N. Shevchenko, Belarusskiy gosudarstvennyy universitet imeni V. I. Lenina)

Atomic Energy Institute im. I. V. Kurchatov, Moscow, Troitsk (Russia)
(Institut atomnoy energii imeni I. V. Kurchatova—IAE)

Belarussian State University im. V. I. Lenin, Minsk (Belarus)
(Belarusskiy gosudarstvennyy universitet imeni V. I. Lenina)

Chemical Physics Institute, USSR/Russian Academy of Sciences, Chernogolovka (Russia)
(Institut khimicheskoy fiziki)

Chemistry and Mechanics Central Scientific Research Institute, Moscow (Russia)
(Tsentral'nyy nauchno-issledovatel'skiy institut khimii i mekhaniki)

Computer [Computational] Center, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)
(Vychislitel'nyy tsentr—VTs)

Continuum Mechanics Institute, USSR/Russian Academy of Sciences, Perm' (Russia)
(Institut mekhaniki sploshnykh sred—IMSS)

Earth Physics Institute im. O. Yu. Shmidt, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut fiziki zemli im. O. Yu. Shmidta—IFZ)

Electrotechnical All-Union Institute, Istra (Moscow Region, Russia)
(Vsesoyuznyy elektrotekhnicheskiy institut)

Engineering Physics Institute, Moscow (Russia)
(Moskovskiy inzhenerno-fizicheskiy institut—MIFI)

Experimental Physics All-Union Scientific Research Institute, Sarov [formerly Arzamas-16] (Russia)
(Vsesoyuznyy nauchno-issledovatel'skiy institut eksperimental'noy fiziki—VNIIEF)

General & Inorganic Chemistry Institute im. N. S. Kurnakov, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut obshchey i neorganicheskoy khimii imeni N. S. Kurnakova—IONKh)

General Physics Institute, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut obshchey fiziki—IOFAN)

High Temperatures Institute, USSR/Russian Academy of Sciences, Moscow, Chernogolovka (Russia)
(Institut vysokikh temperatur—IVTAN)

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)
(Institut gidrodinamiki imeni M. A. Lavrent'yeva)

Krasnoyarsk State University, Krasnoyarsk (Russia)
(Krasnoyarskiy gosudarstvennyy universitet)

Leningrad State University im. A. A. Zhdanov, St. Petersburg [formerly, Leningrad] (Russia)
(Leningradskiy gosudarstvennyy universitet imeni A. A. Zhdanova—LGU)

Machine Science State Scientific Research Institute im. A. A. Blagonravov, USSR/Russian Academy of Sciences, Moscow—branches in St. Petersburg [formerly, Leningrad], Nizhniy Novgorod [formerly Gor'kiy], and Yekaterinburg [formerly, Sverdlovsk] (Russia)
(Gosudarstvennyy nauchno-issledovatel'skiy institut mashinovedeniya imeni A. A. Blagonravova—GNIIM)

Materials Science Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)
(Institut materialovedeniya)

Mathematics Institute, Siberian Branch, USSR/Russian Academy of Sciences, Novosibirsk (Russia)
(Institut matematiki)

Mechanics Scientific Research Institute, at Moscow State University im. M. V. Lomonosov, Moscow (Russia)
(Nauchno-issledovatel'skiy institut mekhaniki, Moskovskiy gosudarstvennyy universitet imeni M. V. Lomonosova)

Mechanics of Solids Institute, Perm (Russia)
(see Continuum Mechanics Institute)

Mechanics Scientific Research Institute, Nizhniy Novgorod [formerly Gor'kiy] (Russia)
(Nauchno-issledovatel'skiy institut mekhaniki)

Military Engineering Academy im. F. I. Dzerzhinsky, Moscow (Russia)
(Voyennaya inzhenernaya akademiya imeni F. I. Dzerzhinskogo)

Mining Institute, Novosibirsk, St. Petersburg [formerly, Leningrad] (Russia)
(Institut gornogo dela—IGD)

Moscow Power Institute, Moscow (Russia)
(Moskovskiy energeticheskiy institut—MEI)

Moscow State Technical University im. N. Ye. Bauman, Moscow (Russia)
(Moskovskiy gosudarstvennyy tekhnicheskiy universitet im. N. Ye. Baumana)

Moscow State University im. M. V. Lomonosov, Moscow (Russia)
(Moskovskiy gosudarstvennyy universitet imeni M. V. Lomonosova—MGU)

Optical Physical Measurements All-Union Scientific Research Institute, USSR/Russian Academy of Sciences, Moscow (Russia)
(Vsesoyuznyy nauchno-issledovatel'skiy institut opticheskikh-fizicheskikh izmereniy—VNIIOFI)

Physical Technical Institute im. A. F. Ioffe, USSR/Russian Academy of Sciences, St. Petersburg [formerly, Leningrad] (Russia)
(Fiziko-tekhnicheskiy institut imeni A. F. Ioffe—FTIAN)

Powder Metallurgy Scientific Production Association (NPO), Minsk (Belarus)
(Belarusskoye nauchno-proizvodst'vennoye ob"yedineniye poroshkovoy metallurgii)

Problems of Mechanics Institute, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut problem mekhaniki—IPM)

Solid-State Physics Institute, Chernogolovka (Russia)
(Institut fiziki tverdogo tela)

Space Research Institute, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut kosmicheskikh issledovaniy—IKI)

Strength Physics & Materials Science Institute, Siberian Branch, USSR/Russian Academy of Sciences, Tomsk (Russia)
(Institut fiziki prochnosti i materialovedeniya)

Strength Problems Institute, Ukrainian Academy of Sciences, Kiev (Ukraine)
(Institut problem prochnosti—IPP)

Synthetic Polymers Institute, USSR/Russian Academy of Sciences, Moscow (Russia)
(Institut sinteticheskikh polimernykh materialov)

Technical Ceramics Interbranch Scientific Research Center, USSR/Russian Academy of Sciences, Moscow (Russia)
(Mezhotraslevoy nauchno-issledovatel'skiy tsentr tekhnicheskoy keramiki—MNTsTK)

Technical Physics All-Union Scientific Research Institute, Chelyabinsk (Russia)
(Vsesoyuznyy nauchno-issledovatel'skiy institut tekhnicheskoy fiziki)

Theoretical Physics Institute im. L. D. Landau, USSR/Russian Academy of Sciences, Chernogolovka (Russia)
(Institut teoreticheskoy fiziki imeni L. D. Landau—ITF)

Tomsk State University im. V. V. Kuybyshev, Tomsk (Russia)
(Tomskiy gosudarstvennyy universitet imeni V. V. Kuybysheva)

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APPENDIX E
FASAC REPORT TITLES

(* asterisk before title indicates report is classified)

(completed)

FY-82/83	*	Soviet High-Pressure Physics Research
		Soviet High-Strength Structural Materials Research
		Soviet Applied Discrete Mathematics Research
	*	Soviet Fast-Reaction Chemistry Research
FY-84		Soviet Physical Oceanography Research
		Soviet Computer Science Research
		Soviet Applied Mathematics Research: Mathematical Theory of Systems, Control, and Statistical Signal Processing
		Selected Soviet Microelectronics Research Topics
	*	Soviet Macroelectronics (Pulsed Power) Research
FY-85		FASAC Integration Report: Selected Aspects of Soviet Applied Science
		Soviet Research on Robotics and Related Research on Artificial Intelligence
		Soviet Applied Mathematics Research: Electromagnetic Scattering
	*	Soviet Low-Energy (Tunable) Lasers Research
		Soviet Heterogeneous Catalysis Research
		Soviet Science and Technology Education
		Soviet Space Science Research
		FASAC Special Report: Effects of Soviet Education Reform on the Military
		Soviet Tribology Research
		Japanese Applied Mathematics Research: Electromagnetic Scattering
		Soviet Spacecraft Engineering Research
		Soviet Exoatmospheric Neutral Particle Beam Research
		Soviet Combustion Research
		Soviet Remote Sensing Research and Technology
		Soviet Dynamic Fracture Mechanics Research
FY-86/89		Soviet Magnetic Confinement Fusion Research
		Recent Soviet Microelectronics Research on III-V Compound Semiconductors
		Soviet Ionospheric Modification Research
		Soviet High-Power Radio Frequency Research
		Free-World Microelectronic Manufacturing Equipment
		FASAC Integration Report II: Soviet Science as Viewed by Western Scientists
		Chinese Microelectronics

(completed/cont'd.)

FY-86/89

Japanese Structural Ceramics Research and Development
System Software for Soviet Computers
Soviet Image Pattern Recognition Research
West European Magnetic Confinement Fusion Research
Japanese Magnetic Confinement Fusion Research
• Soviet Research in Low-Observable Materials
FASAC Special Study: Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion
FASAC Special Study: Defense Dependence on Foreign High Technology
Soviet and East European Research Related to Molecular Electronics
Soviet Atmospheric Acoustics Research
Soviet Phase-Conjugation Research
FASAC Special Study: Soviet Low Observable/Counter Low Observable Efforts: People and Places
Soviet Oceanographic Synthetic Aperture Radar Research
Soviet Optical Processing Research
FASAC Integration Report III: The Soviet Applied Information Sciences in a Time of Change
Soviet Precision Timekeeping Research and Technology
Soviet Satellite Communications Science and Technology
West European Nuclear Power Generation Research and Development
FASAC Special Study: Non-US Artificial Neural Network Research (I)
• Radiation Cone Research in the Former Soviet Union

FY-90/91

Soviet Chemical Propellant Research and Development
Optoelectronics Research in the Former Soviet Union
Parallel Processing Research in the Former Soviet Union
Nonlinear Dynamics Research in the Former Soviet Union
Penetration Mechanics Research in the Former Soviet Union
Foreign Bandpass Radome Research and Development

(in production)

• Foreign Research Relevant to Countering Stealth Vehicles
FASAC Special Study: Non-US Artificial Neural Network Research (II)
Pulsed Power Research in the Former Soviet Union
Climate Research in the Former Soviet Union
Foreign Research in and Applications of Heavy Transuranics
Non-US Data Compression and Coding Research

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