Blast Mitigation Workshop

April 30, 2009

University of Rhode Island

Workshop Organizers:
Arun Shukla, Carl-Ernst Rousseau, & Jimmie Oxley

The thrust of the workshop was in identifying areas of research, as of yet unexplored, and in recognizing hurdles that hinder progress in the field of blast mitigation. This year's workshop focused on two sub-sets: Blast/Fragment/Structure/Interaction and Blast/Pressure/Mitigation. The format of the daylong event consisted of scientific presentations, preceded by keynote addresses from DHS and DoD managers, formulating the security needs they envisioned in the broad area of blast mitigation. These, in turn, acted as focal points to various discussion sessions that followed. We, therefore, tried to effectually strike a balance between presentations and open discussions that we believe optimized the collection of relevant ideas for current and future research. Attendees (50) were from academia, national laboratories, government and industry. A brief report addressing the state of art and future needs that emerged from this workshop are presented here.

Blast Mitigation Workshop

April 30, 2009
The University of Rhode Island

Location: URI Library, 3rd Floor, Galanti Lounge

Organizers: Arun Shukla, Carl-Ernst Rousseau and Jimmie Oxley

Focus Area: Blast/Fragment/Structure/Interaction and Blast/Pressure/Mitigation

Program

8:30 - 8:40	Jimmie Oxley/Arun Shukla: Welcome and Introduction
8:40 - 9-10	Mary-Ellen Hynes (DHS): PLENARY LECTURE
9:10 - 9:25	Hamouda Ghonem & Otto Gregory, URI, Experiments and Modeling of Failure Events of Civil Structures under Blast/Thermal Loadings
9:25 - 9:40	Carl-Ernst Rousseau, URI, Mitigation by Means of Inclusions
9:40 - 9:55	Arun Shukla, URI, Experimental Evaluation of Novel Composite Materials for Blast Mitigation
9:55 - 10:20	Break
10:20 - 10:35	Scott Jackson/Joseph Shepherd, LANL, Caltech, Determination of Explosive Blast Loading Equivalencies with an Explosively Driven Shock Tube
10:35 - 10:50	Choong Shik Yoo & Yogi Gupta, Washington State University, Characterization and Mitigation of Shock Wave on Advanced Materials.
10:50- 11:05	Jason Baird & John Myers, Missouri S&T, Optimal Design and Use of Advanced Structural Materials to Mitigate Explosive and Impact Threats
11:05 - 12:15	*OPEN DISCUSSION* (Moderator/Leader Lee G. Glascoe, LLNL)
12:15 - 1:15	LUNCH
1:15 - 1:45	Bruce LaMattina (ARO): PLENARY LECTURE

1:45 - 2:00	Nancy Sottos/Arijit Bose, University of Illinois/URI, Self-healing Materials for Blast Mitigation
2:00 - 2:15	Mehrdad Sasani, Northeastern University, Science of Progressive Collapse Resistance of Reinforced Concrete Structures
2:15 - 2:30	Tim Harrigan, Foster Miller, Prospects for Adsorption as a Mechanism to Mitigate Low-pressure Blast Waves
2:30 - 2:45	Robert Dye, Los Alamos National lab, Blast Attenuation and Detection System (BADS)”.
2:45 - 3:00	BREAK
3:00 - 3:15	Steven F. Son, Purdue University, Blast Mitigation for Protection against Blast Induced Trauma
3:15 - 3:30	Najib Abboud, Weidlinger Associates Inc., Blast Vulnerability in Tunnels and Civil Structures
3:30-3:45	William Fourney, University of Maryland, Model Testing on Mitigation Techniques
3:45 - 5:00	*Discussion and Closing Remarks:* (Moderator/Leader Joseph DiVito, Raytheon)
6:00	DINNER, Spain Restaurant (Narragansett)

Succint Overview of Workshop

The workshop featured two plenary speakers, Dr. Mary Ellen Hynes of the Department of Homeland Security (Science and Technology Division) and Dr. Bruce LaMattinna of the Department of Defense (ARL/ARO). Both lectures set the tone for the need of a basic science agenda to counter the IED threat to the public and to civil infrastructure, on the one hand, and on the battlefield, on the other hand. These were followed by presentations from academic contributors (see the attached agenda) then by a focused discussion session led by Dr. Lee Glascoe of Lawrence Livermore National Laboratory. Afternoon presentations were delivered by representatives from industry, government, the national laboratories, and academia not currently affiliated with the center. Afternoon presentations were followed by a final discussion session led by Dr. Joseph DiVito of Raytheon Corporation.

<u>Goals of workshop</u>

The thrust of the workshop was in identifying areas of research, as of yet unexplored, and in recognizing hurdles that hinder progress in the field of blast mitigation.The workshop was intent on outlining concepts to help overcome the fundamental hurdles involved in countering the IED threat. Attendees from across the research spectrum (academia, industry, federal government, national laboratories) sought to define basic research needs, highlight current research deficiencies, and outline opportunities to build a consistent and productive basic research agenda. Such initial discussion is necessary to begin to segment the space of threats and vulnerabilities to best guide the thrust of basic research efforts while encouraging interagency collaboration.

<u>Major findings</u>

The presentations addressed various means of mitigating the Improvised Explosive Device (IED) threat through the study of composites, as well as better understanding of construction materials, of scaling, of blast phenomenology, and of structural and system performance in response to blast loading. The two group discussion sessions attempted to underline certain basic research needs necessary to define future efforts. Generally speaking, countering the IED threat through blast mitigation presents several fundamental hurdles that can principally be associated with:

- The site- and system-specific nature of the majority of the threat and vulnerability conditions, and
- The required integration of capabilities across a wide range of technical fields including materials science, mechanics, dynamics, sensing and controls, computational analysis, uncertainty quantification, and chemistry.

<u>Proposed research directions</u>

Materials requirements

The nation has a large, intricate, varied, and yet, vulnerable infrastructure system that is in turn composed of several smaller systems. The requirements to protect such a system and its components from a threat, including an explosive threat, can be examined in terms of systematic *resiliency*. Resiliency here is defined as the ability of a threatened system to prevent, sustain, and recover functionality in time, preferably very rapidly, after successful execution of the threat. Thus, a more resilient infrastructure is better able to recover from both natural and man-made disasters, is less susceptible to disruption, and is, ultimately, less attractive to attack. When viewed in terms of improving overall infrastructure resiliency, the requirements of a basic research agenda may be formulated. For example, one requirement may be a systematic baseline of fundamental construction material properties establishing current system resilience; another requirement may be that mitigative material improvements should be optimized across a wide a range of threat and vulnerability configurations as possible to improve a structural system's overall resiliency.

Areas of deficiency

While considering the requirements for a basic research agenda, a list of general but tractable deficiencies in current research efforts can be highlighted for further study and improvement. Some current deficiencies include the following:

- Experimental data under relevant conditions (*e.g.*, high rates, high temperatures, and high pressures);
- Proper formulation for damage mechanics for a range of constitutive models – including fracture and fragmentation – under the same extreme conditions;
- Suitably integrated, multi-scale simulation tools; and
- Higher-fidelity embedded sensing to allow for active mitigation schemes.

Collaborative and research opportunities

Competing demands lead to competing directions in research that can provide constraints to research, but can also offer opportunities for success through cross-leveraging. On one extreme, engineers and contractors working for owner/operators are under pressure to develop near-term mitigation schemes that can apprehend a wide range of threats while maximizing deployability and minimizing cost. On the other end of the spectrum, the academic community seeks novel contributions in basic research areas including material science (so-called "materials on demand") and sensing. Such novel contributions are associated with longer range planning against a wide range of threats and can promote future possibilities, but often with limited attention to specific current vulnerabilities. Between academia and industry, the national laboratories are well suited to function as a liaison to close critical gaps between basic research efforts and the engineering efforts necessary to advance the state of blast mitigation.

<u>Overall challenge to the center</u>

Inter-agency leveraging, and inter-disciplinary cooperation were emphasized as an effective means of defining and achieving a successful basic research agenda. Several specific research areas were highlighted during the workshop with emphasis on the importance of

- Proper multiscale modeling (with minimal abstraction) that can accommodate for important small scale effects (inclusions) and their role on larger scale events (structural collapse);
- High-fidelity embedded sensing for active mitigation schemes;
- Uncertainty quantification and component and system validation; and

•Fundamental materials characterization (current materials, novel composites) to provide properly defined equations of state.

Additionally, inventive concepts borrowed from peripheral fields, including biological, ecological, and biomimetics were discussed as possible areas that could provide value to a successful counter-IED research program.

To formulate an effective path forward, it was clear that there is a need to "orthogonalize" the space of blast threats and structural vulnerabilities, to devise a reasonable set of axes over which to segment the continuum of threats and vulnerabilities. One possible orthogonalization is to develop mitigation design specifications for each class of vulnerability. Once established, issuing *Grand Challenges* to address each vulnerability class could stimulate crosscutting research efforts. Each Grand Challenge would consist of a design of experiments that address the deficiency of data associated with each Challenge for validation and verification of material models and simulation tools. Many, if not all, Challenges would entail novel material design, and structural or configuration design. Possible gains from such a Challenge may be, for example, from the perspective of materials design, a "wish list" of critical material properties where the development of novel composite systems that incorporate absorptive or self-healing materials may rate high on such a wish list.

Summary of Presentations

The overwhelming majority of the presentations focused either on the search for ideal material systems, or on experimentations conducted on current materials and structures. The goal in each case was to evaluate their worthiness in fulfilling mitigatory functions. The diversity of choice thus made it clear that no single material can successfully fulfill the mitigation needs associated with all loading conditions and circumstances. Next, follows an enumeration of the material systems introduced and the conditions identified that can most effectively exploit their properties.

<u>Traditional materials</u>

Two of the featuring research cases examined the behavior of building materials as they undergo extreme loading conditions. This is motivated by the need a achieve a thermal and dynamic understanding that is not available at this time.

Structural steel

Next to concrete, structural steel is the most common material used in skyscrapers. Yet at present, its properties under hostile conditions have not been properly cataloged. It is known to provide strength, flexibility, and tensile capabilities to the concrete, which possesses none of these attributes. However, under highly elevated temperatures such as experienced during the World Trade Center Twin Tower collapse, these desirable properties vanish, leaving the concrete vulnerable. It is, therefore, imperative that these steels be evaluated at the corresponding high temperatures to develop an understanding of the modes of failure present in buildings in such an environment. Remedial action can thus be retrofitted in to the edifice. For future constructions, the discovery of alloys less susceptible to high temperature degradation may also arise and be introduced into these structures.

Primary failure modes of buildings

At present, the overall structural robustness of structures is being studied by systematically instrumenting buildings targeted for demolition throughout the country. The present effort consists in locating critical locations, understanding modes of failure, identifying deformation, deflection, or stress patterns of these structures. In most of these cases, this is accomplished by strategically placing explosive charges to achieve the desired damaging conditions.

<u>Novel composite materials</u>

Most of the research thrust revolved around a process of discovery of new materials or uncovering attributes of recently developed model material that make them suitable as shields.

Understanding of novel composites

Novel composites have proven to be highly effective in shielding against explosions and fragmentation. They have been used mostly within military contexts and are currently being promoted by the Army and the Navy. They include epoxy based material systems that are coupled with glass and carbon fibers, kevlar, graphite, ceramics, 2-D and 3-D woven fibers. Evaluation of these hybrid materials and sandwich constructions are being conducted using, primarily, explosive charges, shock tube loading, and penetration studies. Their fabrication is, in most cases, far too specialized for manufacturing within academic settings. Therefore, many of these composites are produced by industrial companies with direct DOD contract. They have, in turn, submitted their materials to universities for evaluation. Understanding of their behavior is conducted by simultaneous monitoring by high-speed-photography, and measurement of displacement, deformation, stress, and strain, accompanied by post-mortem assessment. Based on careful evaluation of damage mechanisms novel designs are proposed for the fabrication of better performing structures.

Understanding the role of inclusions

Fundamental studies are also being applied, at the micro-structural level, to understand the mechanisms that lead to failure and, in consequence, the means by which it can be avoided. This is being done by insertion of various geometries, concentration, and configurations of particulates into a matrix, and studying their influence on the modes of failure and energy dissipation at different high loading rates that correspond to environment encountered during explosive settings.

Development of expendable and/or 'green' shields

As environmental consciousness advances at all political and societal levels, ideas emanating from environmentally friendly materials are also surfacing. One such example consists in coupling *green* materials with concrete in various protective scenarios. The proposed *green* materials include fly-ash, wood, poly-urea. These materials are soft and suffer degradation with time, but are being proposed as *sacrificial* materials to be easily discarded depending on ambient conditions or existing needs. Also, preliminary research shows that hybrids that include combinations of concrete, poly-urea, and chopped glass fibers appear to be of the most promising kind, achieving density reduction of 40% over pure concrete. They are currently being testing using blast loading.

Is ductile metallic glass achievable?

Bulk metallic glass has been studied intensely over the past two decades. Its brittleness is quite apparent, preventing ready suitability to impact conditions. Experiments are being conducted at present using micro pulsing, and fragment impact to evaluate improvement in ductility that could be brought about with the introduction of additives, such as zirconium, hafnium, and possibly others, as research and understanding of the material progresses.

Material recovery through self-healing

The attractive idea of self-healing materials is also becoming manifest, not yet readily in the context of prevention, but as a reconstructive means. Capsules embedded within a matrix, release their content, upon fracture of the latter, forgoing the need for active repair. The concept is currently being applied to polymers and concrete.

<u>Explosive environment</u>

Within the explosive environment, two objectives have been identified, namely the development of scaling rules that will lead to accurate experimentation, and the instantaneous identification of an explosive signature able to trigger shielding mechanisms into an active mode.

Development of accurate scaling of explosions

Several of the studies relate to the nature of the explosive environment, and the means by which they can be duplicated by full-scale experiments, reduced-scale laboratory experiments, theoretical predictions, and currently available numerical tools. The researchers have shown scaling techniques, in particular, to be highly effective and accurate, thereby reducing cost, time to completion of experiments, and improved safety.

Shielding initiation by means of radio frequency broadcast

A novel idea in the field, consists in capturing the radio frequencies emitted during the detonation/explosion process, prior to the blast reaching a structure. This automatically triggers and instantaneously results in the self-deployment of a shielding mechanism. The latter can be as simple as the spraying of water and mist, a circumstance which has astonished researchers, recently, by the level of attenuation it imposes on a blast. Chemical adsorption as a mechanism for reducing the blast overpressure was also discussed.

Safety agencies' viewpoint

Two government agencies were represented at the symposium and provided keynote lectures, the Department of Homeland Security and the Department of Defense. Representatives of these agencies provided views, within their respective programs, of the mitigation needs they envision.

DHS: How can we improve the nation's infrastructure?

Collapse - Not an option

Experience has shown that building collapse relates directly to the death of the occupants. Thus, the primary purpose of a mitigation group should be in preserving the integrity of the overall building structures. It is well understood also, that experimentation is necessary. However, the development of predictive codes must also gain priority in order to perform accurate, immediate, and swift safety assessments as critical cases arise.

Shield materials must be structure specific

Researchers must also be cognizant of the fact that the use of similar or identical materials in different structures will not yield similar results. It is evident, for instance, that building and bridges, tough both made of concrete and structural steel, will behave differently. Likewise, experimentation has shown that shields used in some applications have proven, in certain cases, to be harmful when utilized to mitigate explosions near bridges.

Need for anticipation of deteriorated conditions of structures

Other considerations consist in anticipating future degradation, as in the case of obvious corrosion in underwater tunnels. Researchers must also examine unusual loading cases that are nonetheless probable, such as underground or underwater explosions. Researchers should think of innovative solutions, such as camouflaging or optical illusion techniques that can be used in diminishing the visual prominence of buildings.

DOD (ARO): Improvement in materials shielding

Primarily a materials driven approach

The design landscape does not solely consist in inventing new materials, but also in applying existing materials to different environments. Researchers must always seek new applications and uses for them. Conversely, it must be recognized that no single material can be made to be applicable to all loading conditions. It is believed that the field of mitigation is currently, and will always be, constrained by the necessity of optimizing materials specifically for distinct loading ranges, loading modes, loading rates, and failure modes.

Need to understand basic material behavior beyond functionality

It has been observed that most damage research is phenomenological and does not include the materials' behavior at the microstructural level. There is, consequently, a lack of basic physical understanding of these materials. Another area of weakness has also been identified in the lack of understanding of the effect of dynamic loading on human beings. Researchers should seek to fill that void by engaging in multi-physics research, and cross-linking across the various boundaries of science. Finally, there should be an effort to couple blast and fragmentation impact within the same experiments, in addition to the basic understanding of their individual effects.

Discussion Sessions

Two separate discussion sessions were conducted, and initiated with the following question: Is there a way to leverage the capabilities of the Center's Mitigation Group with existing efforts geared toward Counter-Improvised-Explosive-Devices (CIED)?

<u>Improved Networking</u>

The answer to the above question is thought to lie in facilitating communication with various entities that use, own, produce equipment or materials used for CIED purposes. Such entities would include primarily owner-operators and government agencies such as LANL, LLNL, ARL, where unpublished research is being conducted. The fostered interaction would enhance the breath of understanding of existing mitigation needs by both university and government researchers. It is also proposed that Broad Agency Announcements (BAA) be used as a guideline in setting the tone of the center's research. The formation of working groups is also proposed, with the cautionary note that it is difficult to instill a sense of proprietorship in the participants, the obvious drawback being that, often, little is accomplished.
Finally, the idea of data gap analysis, which is partly the aim of this workshop, is also recommended.

<u>A Materials Approach</u>

A large part of the discussion focused on the idea of material resilience as a means of effecting mitigation. What is a resilient material? Ample discussion concluded on the following definition: *A resilient material is one that performs well under combined and extreme environment, possesses increased strength and ductility, is resistant to aging, and is light.*
These are properties that should universally be sought in every mitigating material.

The means of achieving so are not always evident. However, the following concepts were advanced: Active systems should be incorporated whenever possible. Biomimetics should be integrated in our designs. Consideration should be given to the use of novel absorptive materials. It is emphasized again, here, that the identification of a single material that will perform efficiently across all loading regimes, loading conditions, and scales is highly improbable. Finally, the loading of concern being frequently within the ballistic range, the equations of state for the materials under study should be developed.

<u>Establish Comprehensive Goals</u>

Priorities must be set as to the relevance of *scales, phenomena, time of loading periods* that are considered most appropriate. The center should also provide directions on the classes of problem that should be addressed, while making sure that innovation is not stifled. There must also be a constant refocusing from *individual problems* set by individual researchers to the solution of *global challenges* that constitute the aim of the center. The center should also consider the performance of risk analysis as a means of prioritization, by identifying areas most likely to become vulnerable, and thus guide research in those directions.

Need for research extension into air- and water-ways structures

Commendable progress has been achieved in modeling some of the land-based infrastructures through controlled testing and in successful prediction of their dynamic response to blast loads. However, we have yet to achieve similar level of progress with blast mitigation efforts related to air and water based transportation system infrastructures. One of the reasons for this shortcoming may be attributed to inadequacy in knowledge-based selection/prioritization of new generation material systems capable of complying with operational constraints such as low-density, low-cost, high strength/fracture toughness, while offering great potential toward withstanding blast pressure, shock holing, fragmentation, and fire. Composites that have been exploited for blast mitigation applications, however, result in excessive weight and their cost have rendered them generally unacceptable to the transportation industry, especially to the airline industry. DHS is still looking for innovative use of next generation composite/hybrid composite/fiber-metal laminate and novel designs to meet these challenges.

Improved collaboration and in-center interaction

Different approaches should be sought in seeking solutions to individual problems. The relevant results from the various investigative sources and methodologies should then be compared. Likewise, new codes must be implemented and validated. It is recognized also that fundamentals of materials behavior must be better understood, therefore incorporated in the overall purpose of the research. Structural concerns can subsequently be scaled from the fundamentals.

Data Gaps, Recommendations, and Future Directions

Based on the presentations and discussions that followed, several areas of research for blast mitigation were identified where data gaps exist and these are listed below:

- Blast overpressure dampening by utilizing water mist or other methods.
- Development of resilient self healing materials.
- Understanding failure mechanisms in and developing engineering failure models for novel composite blast resistant materials.
- Development of novel metallic and composite sandwich structures for energy absorption and structural integrity under blast loading.
- Understanding structural collapse mechanisms, including the effect of elevated temperatures on structural steel, and developing numerical codes to predict structural collapse.
- Understanding key material attributes that improve the response of structures under simultaneous blast and fragment impact.

- Understanding the shattering of glass and developing glass that is both blast resistant and energy efficient.
- Understanding stress wave scattering and attenuation due to particulates for better dampening and channeling of energy.
- Addressing scaling issues to take lab scale experiments to real life.
- Development of expendable or sacrificial shields.
- Development of active shielding systems, including triggering through radio frequency broadcast.
- Economical and efficient processing capabilities for large composite structures.

Building a successful and meaningful basic research agenda will require cooperation across disciplines, across agencies and across institutions. The DHS Centers of Excellence consisting of academic, national laboratory, and industry partners offer a valid foundation from which to build such a basic research agenda. In our opinion, the workshop of April 30, 2009 at the University of Rhode Island successfully began the discussions needed to move this collaborative process forward.

As a result of the worshop and the identification of the numerous Data Gaps listed above, three new projects were initiated and have now been added to the mitigation activities of the center. These include the study of the blast overpressure dampening capabilites of water mist lead by Prof. Steven F. Son (Purdue), and the study of the effectiveness of self-healing materials within two different types of structures. This collaborative effort will be lead by Prof. Nancy Sottos (University of Illinois) and Prof. Arijit Bose (University of Rhode Island).

Finally, based on the discussions about cynergies between the center and goverment agencies, we have initiated talks with the Lawrence Livermore National Laboratories and the Los Alamos National Laboratory, about engaging into direct collaboration in mitigatives activities.

Future Meeting

The next meeting will be a "Blast Mitigation Symposium" that will be organized as a part of IMPLAST 2010 in Providence RI from October 12-14.

List of Attendees

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Power Point Presentations

Power point presentations of the talks given at the workshop are attached.

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LLNL Perspectives on the Blast Mitigation Workshop
University of Rhode Island
April 30, 2009

Report by Lee Glascoe and Joel Bernier
Lawrence Livermore National Laboratory

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Auspices Statement

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High-level Overview

The plenary speaker, Mary Ellen Hynes of DHS/S&T, kicked off the workshop with a concise overview of several relevant DHS-funded research efforts and set the tone for the need of a basic science agenda to counter the IED threat to the public and to civil infrastructure. After the plenary seminar, the morning session of technical talks commenced with presentations from academic contributors (see the attached agenda) followed by a focused discussion session led by Lee Glascoe of Lawrence Livermore National Laboratory. After lunch the conference resumed with an afternoon session of presentations by representatives from industry, government, the national laboratories, and academia. The afternoon session in turn was followed by a final discussion session led by Joseph DiVito of Raytheon Corporation.

Findings and Goals

The technical talks were largely concerned with mitigating the IED threat through better understanding of construction materials, through study of composites, through a better understanding of scaling, through a better understanding blast phenomenology, and through a better understanding of structural and system performance in response to blast loading. The two group discussion sessions attempted to underline certain basic research needs necessary to define future efforts. Generally speaking, countering the IED threat through blast mitigation presents several fundamental hurdles that can principally be associated with

(1) the site- and system-specific nature of many (but not all) of the threat and vulnerability conditions, and
(2) the required integration of capabilities across a wide range of technical fields including materials science, mechanics, dynamics, sensing and controls, computational analysis, uncertainty quantification, and chemistry.

The goal of this workshop was to begin outlining a pathway for overcoming these fundamental hurdles. Attendees from across the research spectrum (academia, industry, federal government, national laboratories) sought to define basic research needs, highlight current research deficiencies, and outline opportunities to build a consistent and productive basic research agenda. Such initial discussion is necessary to begin to segment the space of threats and vulnerabilities to best guide the thrust of basic research efforts while encouraging interagency collaboration.

Requirements, Deficiencies, and Opportunities

The nation has a large, intricate, varied, and yet, vulnerable infrastructure system that is in turn composed of several smaller systems. The requirements to protect such a system and its components from a threat, including an explosive threat, can be examined in terms of systematic *resiliency*. Resiliency here is defined as the ability of a threatened system to prevent, sustain, and recover functionality in time after successful execution of the threat. Essentially, a more resilient infrastructure is better able to recover from both natural and man-made disasters, is less susceptible to disruption, and is, ultimately, less attractive to attack. When viewed in terms of improving overall infrastructure resiliency, the requirements of a basic research agenda may be formulated. For example, one requirement may be a systematic baseline of fundamental construction material properties establishing current system resilience; another requirement may be that mitigative material improvements should be optimized across a wide a range of threat and vulnerability configurations as possible to improve a structural system's overall resiliency.

While considering the requirements for a basic research agenda, a list of general but tractable deficiencies in current research efforts can be highlighted for further study and improvement. Some current deficiencies include the following:

- Experimental data under relevant conditions (*i.e.*, high rates, high temperatures, and high pressures);
- Proper formulation for damage mechanics for a range of constitutive models – including fracture and fragmentation – under the same extreme conditions;
- Suitably integrated, <u>multi-scale</u> simulation tools; and
- Higher-fidelity embedded sensing to allow for active mitigation schemes.

Competing demands lead to competing directions in research that can provide constraints to research, but can also offer opportunities for success through cross-leveraging. On one extreme, engineers and contractors working for owner/operators are under pressure to develop near-term mitigation schemes that can apprehend a wide range of threats while maximizing deployability and minimizing cost. On the other end of the spectrum, the academic community seeks novel contributions in basic research areas including material science (so-called "materials on demand") and sensing. Such novel contributions are associated with longer range planning against a wide range of threats and can open up future possibilities, but often with limited attention to specific current vulnerabilities. Between academia and industry, the national laboratories are well suited to function as a liaison to close critical gaps between basic research efforts and the engineering efforts necessary to advance the state of blast mitigation.

Highlights and Challenges

Inter-agency leveraging, inter-disciplinary cooperation, and inter-lab partnership was emphasized as the best way to define and realize a successful basic research agenda. Several specific research areas were highlighted during the talks and discussion sessions with emphasis on the importance of

(1) proper multiscale modeling (with minimal abstraction) that can accommodate for important small scale effects (inclusions) and their role on larger scale events (structural collapse)
(2) high-fidelity embedded sensing for active mitigation schemes,
(3) uncertainty quantification and component and system validation, and
(4) fundamental materials characterization (current materials, novel composites) to provide properly defined equations of state.

Additionally, out of the box considerations including biological, ecological and biomimetics were discussed as possible areas that could provide value to a successful C-IED research program.

To formulate an effective path forward, it was clear that there is a need to "orthogonalize" the space of blast threats and structural vulnerabilities, to devise a reasonable set of axes over which to segment the continuum of threats and vulnerabilities.

One possible orthogonalization is to develop mitigation design specifications for each class of vulnerability. Once established, issuing *Grand Challenges* to address each vulnerability class could stimulate crosscutting research efforts. Each Grand Challenge would consist of a design of experiments that address the deficiency of data associated with each Challenge for validation and verification of material models and simulation tools. Many, if not all, Challenges would entail novel material design, and structural or configurational design. Possible gains from such a Challenge may be, for example, from the perspective of materials design, a "wish list" of critical material properties where the development of novel composite systems that incorporate absorptive or self-healing materials may rate high on such a wish list.

Building a successful and meaningful basic research agenda will require cooperation across disciplines, across agencies and across institutions. The DHS Centers of Excellence consisting of academic, national laboratory and industry partners offer a valid foundation from which to build such a basic research agenda. In our opinion, the workshop of April 30, 2009 at the University of Rhode Island successfully began the discussions needed to move this collaborative process forward.

Blast Mitigation Workshop

April 30, 2009
The University of Rhode Island

Location: URI Library, 3rd Floor, Galanti Lounge

Organizers: Arun Shukla, Carl-Ernst Rousseau and Jimmie Oxley

Focus Area: Blast/Fragment/Structure/Interaction and Blast/Pressure/Mitigation

Program

8:30 - 8:40	Jimmie Oxley/Arun Shukla: Welcome and Introduction
8:40 - 9-10	Mary-Ellen Hynes (DHS): PLENARY LECTURE
9:10 - 9:25	Hamouda Ghonem & Otto Gregory, URI, Experiments and Modeling of Failure Events of Civil Structures under Blast/Thermal Loadings
9:25 - 9:40	Carl-Ernst Rousseau, URI, Mitigation by Means of Inclusions
9:40 - 9:55	Arun Shukla, URI, Experimental Evaluation of Novel Composite Materials for Blast Mitigation
9:55 - 10:20	Break
10:20 - 10:35	Scott Jackson/Joseph Shepherd, LANL, Caltech, Determination of Explosive Blast Loading Equivalencies with an Explosively Driven Shock Tube
10:35 - 10:50	Choong Shik Yoo & Yogi Gupta, Washington State University, Characterization and Mitigation of Shock Wave on Advanced Materials.
10:50- 11:05	Jason Baird & John Myers, Missouri S&T, Optimal Design and Use of Advanced Structural Materials to Mitigate Explosive and Impact Threats
11:05 - 12:15	*OPEN DISCUSSION* (Moderator/Leader Lee G. Glascoe, LLNL)
12:15 - 1:15	LUNCH
1:15 - 1:45	Bruce LaMattina (ARO): PLENARY LECTURE

1:45 - 2:00	Nancy Sottos/Arijit Bose, University of Illinois/URI, Self-healing Materials for Blast Mitigation
2:00 - 2:15	Mehrdad Sasani, Northeastern University, Science of Progressive Collapse Resistance of Reinforced Concrete Structures
2:15 - 2:30	Tim Harrigan, Foster Miller, Prospects for Adsorption as a Mechanism to Mitigate Low-pressure Blast Waves
2:30 - 2:45	Robert Dye, Los Alamos National lab, Blast Attenuation and Detection System (BADS)".
2:45 - 3:00	BREAK
3:00 - 3:15	Steven F. Son, Purdue University, Blast Mitigation for Protection against Blast Induced Trauma
3:15 - 3:30	Najib Abboud, Weidlinger Associates Inc., Blast Vulnerability in Tunnels and Civil Structures
3:30-3:45	William Fourney, University of Maryland, Model Testing on Mitigation Techniques
3:45 - 5:00	*Discussion and Closing Remarks:* (Moderator/Leader Joseph DiVito, Raytheon)
6:00	DINNER, Spain Restaurant (Narragansett)