NEW MEXICO EPSCOR
STRUCTURAL HEALTH MONITORING AND SELF-HEALING OF AEROSPACE STRUCTURES

Final Report
Grant number: NNX07AT64A
Structural Health Monitoring of Aerospace Structures

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October 1, 2010 – September 30, 2011
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Grant Number NNX07AT64A

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New Mexico NASA EPSCoR - NNX07AT64A
Progress Report

Research accomplishments measured against the proposed goals and objectives:

Objective #1: Develop a methodology for in-situ health monitoring and damage detection of aerospace structures using low frequency vibration and electrical conductivity measurements combined with high frequency embedded nonlinear ultrasonic wave interrogation.
Two new approaches were proposed for structural health monitoring of aerospace structures. The first is to treat SHM as a comprehensive, multi-scale phenomenon in which damage detection may be needed over a spectrum of length scales from the microscopic to the macroscopic (Butcher, Sevostianov, Zagrai). The second approach is attributing to damage in joints and connections an importance commensurate with fracture and fatigue damage that develops in the structural material (Burton, Butcher, Sevostianov). The research outcomes will be useful for many aerospace structures, including aircraft structures and engines, launch vehicles, space vehicles, permanent structures placed on the moon or Mars, and robotic devices that patrol these structures for SHM.

Accomplishments on Objective #1:

1. A new methodology for detecting a self-loosening failure in bolted joints that uses electrical resistance as a diagnostic parameter has been developed. It is based on the phenomenon that the electrical constriction resistance of the rough contact interface between two conductive members clamped by the bolt is a sensitive indicator of bolted joint integrity. A simple formula for relationship between relative electrical conductance changes and relative tightening torque changes is analytically obtained. The effects of rough surfaces on the micro-slip of bolted joints have been studied by linking microscopic surface roughness parameters to macroscopic parameters in parallel–series Iwan models. This has lead to analytical expressions for the energy dissipated in bolted joints, for instance, in terms of these tribological parameters.

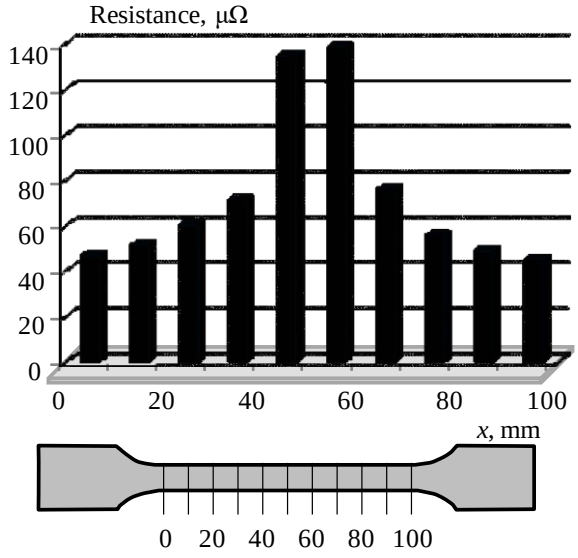

Figure 1. Variation of local resistance in a specimen after 44000 loading cycles. Note substantial increase of resistance (drop of conductivity) near the notch, where the clusters of microcracks are suspected.

2. A new concept for monitoring of strength reduction due to accumulated damage has been proposed and verified (experimentally and numerically). The key parameter for monitoring is not the reduction of the average (over the specimen) stiffness but its *local* minimal values caused by formation of defect clusters. These defect clusters can be identified by the emergence of spatial *gradients* of elastic stiffness on a smaller scale. A convenient tool of detecting these gradients is provided by the elasticity-conductivity connection: the electric conductance gradient is usually easier to measure than the stiffness gradient.

3. A novel method of reduced order modeling using an iterated Local Equivalent Linear Stiffness Method and Ritz vectors, which is comparable in accuracy to widely used Principal Orthogonal Decomposition (POD) technique but avoids the need for *a priori* simulation of the mathematical model, has been tested and has demonstrated promise for SHM applications with combined joint/material damage. A combined finite element/ harmonic balance analysis has been used to detect the locations and depths of cracks in rotating shafts by analyzing the changes in the forward and backward whirl frequencies. New models of breathing functions for cracked rotating shafts has been developed which represent the time-varying change in local stiffness and area moment of inertia much better than in the previous literature. This theoretical and computational work has been validated experimentally using a SpectraQuest rotordynamic system.

4. A methodology has been developed to distinguish between damage accumulated in structural members and in joints. It is based on the combined approach of conductivity and natural frequency measurements. Explicit formulas have been obtained for the one-dimensional case of longitudinal vibrations of a slender bar. In addition, several novel methods of reduced order modeling (POD, Ritz vectors) have been tested and have demonstrated promise for SHM applications with combined joint/material damage. Specifically, explicit formulas have been obtained for the case of transverse vibrations of a clamped uniform beam with a damaged boundary, and two approximation methods (based on Chebyshev polynomials and perturbation analysis) have been used for non-uniform beams and columns with damaged boundaries. Furthermore, an optimization method allows the determination of boundary damage parameters given the natural frequencies. In addition, the procedure of using a Chebyshev spectral collocation technique has been extended to the case of three-dimensional vibrations of thick rectangular plates with one or more damaged boundaries in which it was shown how the frequencies associated with dilatational and shear modes are affected by the presence of boundary damage, as well as for anisotropic Kirchoff plates. Furthermore, the method of structural damage interrogation by exciting a structure with a hyperchaotic signal has been further developed by using a new feature of the geometry of the driving and output attractors, called the nonlinear prediction error. By increasing the number of positive Liapunov exponents in the input driver it was found that this allows the trajectory to more fully explore the phase space and thus is a more sensitive damage metric which clearly shows the benefits of hyperchaotic interrogation over traditional interrogation methods using deterministic, random, or even chaotic signals. Experimental verification of this technique has been done in the Structural Engineering Department Laboratory at the University of California at San Diego.

5. Vibration based experimental program has been completed. The measurement system consists of very light accelerometers mounted at several locations on the specimens. The data gathering system is operational for impulse testing. The capability to test a cantilever-free beam with non-ideal cantilever boundary conditions is operational; here the tightening torque on the bolted, cantilevered end can be controlled to simulate ideal and varying levels of non-ideal connection. Experimental data allowed us to determine the effect of non-ideal connection on the modal damping parameters and test the hypothesis that damping can be used as a discriminant to characterize connection joint/connection damage.

6. Electromechanical impedance method and nonlinear resonance measurements have ben applied to high frequency detection of incipient fatigue damage in aluminum alloy specimens. In this study, the electromechanical impedance method is utilized for assessment of material deterioration under cyclic fatigue loads. Piezoelectric wafer active sensors were utilized for transmission and reception of elastic waves. Variations in structural dynamic characteristics were considered for different excitation conditions and increasing damage severity. Two-dimensional aluminum specimens were subjected to increasing fatigue cycles at stress amplitudes below the yield point, and electromechanical impedance signatures were taken at discrete levels of fatigue damage. Linear and nonlinear features of the impedance signatures were compared for different damage conditions. Spectral measurements demonstrated that the downward frequency shift dependency observed in 1-D dog bone specimens with increasing fatigue levels is also apparent in 2-D structures undergoing fatigue. As in the previous experiments with 1-D samples, it was observed in the 2-D specimens that the frequency shifts occurred before the appearance of a visible crack, which indicates the method's sensitivity to incipient fatigue damage before crack initiation and growth. The changes in average amplitude level for the impedance analyzer low-frequency and high-frequency tests also correlate with the increased level of fatigue. Nonlinear harmonic measurements were conducted on fatigued aluminum samples. A general increasing trend was observed for the second harmonic amplitude data, which would indicate increasing levels of material nonlinearity, but consistency of the data needs to be verified in future tests. We observed qualitative correlation between changes in EMI response, electrical resistance and strength reduction in damaged specimen.

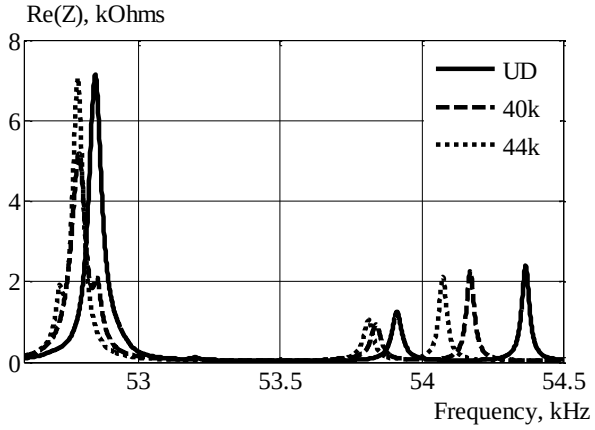

Figure 2. Real part of EMI corresponding to intact (undamaged – UD) conditions and after 40,000 and 44,000 cycles.

Objective #2: Develop self-repairing materials for aerospace structures subjected to accumulated damage and use the proposed SHM methods to monitor the self-healing process.

Accomplishments on Objective #2:

1. A self-healing thermal barrier coating on the Nb and Mo monocrystals and low alloyed Cr bulk samples coated with Fe-45%Cr-4%Al-1%Ni-0.3%RE (La, Y) alloy using EB-PVD technique. has been developed. SEM, WDS, AES and LM investigations were carried out. The following results were obtained:
   - The refractory metals base metal/metal composition with an overlay coating of heat resistant alloy of ultra-fine grain structure after the pre-oxidation at $1200^{O}C$ transforms into the combined metal/metal/ceramic compositional material of the sandwich structure as association the multi-layer architecture of hybrid materials with the distributed different functional behaviors.
   - The metallic-oxide hybrid layer formed on the surface of synthesized compositions at high working temperatures has an ability to heal the cracks developed as a result of the mechanical and thermal damages.
   - Ultra-fine crystalline structure of both, the overlay coating and the self-organizing TGO protective scale on its surface, provide the relaxation of those stresses caused due to the thermal-expansion mismatch during the co-deformation of metallic matrix with nano-scale crystalline layers (minimizing the probability for crack initiation) and promoting a smooth transition between three regions having different physical-mechanical behaviors.
   - The realization of considered structural architecture of the different materials combination, generally, for the obtained compositional material is expressed in the possible collective effects such as: increasing in the damage tolerance, the ability of cracks for the thermally activated self-healing, and the optimal combination of high values of heat resistance and heat proofness.

2. Based on this composite material, following three primary regions of oxidation process can be identified: (I) Fe_2O_3/Fe_3O_4 external scales + Cr_2O_3/Al_2O_3 internal scales, (II) $Cr_2O_3/Fe(Cr, Al)_2O_4$ external scale + Al_2O_3 internal scales and (III) external scale of only Al_2O_3. The role of the high chromium content in producing TGO Al_2O_3 scales at such lower aluminum content and then in binary Fe-Al alloys can be described by considering the transient oxidation phenomena for a Fe-45%Cr-4%Al-0.3%La at $1200^{O}C$ shown schematically in Figure 3. The initial oxide scale (Figure 3a) contains all the cations of the alloys surface which is composed of the mixture of the nanocrystallite oxides $Cr_2O_3/Al_2O_3/Fe_2O_3$ (Figure 3b). The subscale formation of Al_2O_3 occurs because it is stable at the low oxygen activity defined by the mixture of $Cr_2O_3/Fe(Cr,Al)_2O_3$ alloy equilibrium and internal oxidation of Al occurs ahead of this front since Al_2O_3 is stable at even lower oxygen activities here. The high chromium content results in a Cr_2O_3 subscale, which may be continuous (Figure 3c) and defines a lower scale-alloy oxygen activity. It reduces the oxygen diffusion, and curtails internal Al_2O_3 formation. Further growth of $Cr_2O_3/Fe(Ce,Al)_2O_4$ will be blocked. Eventually, the Al_2O_3 subscale becomes continuous and its rate will be controlled. Thus, on the surface of the alloy specimen with a Beilby layer at $1200^{O}C$, conditions for scale formation even at the initial stages of the oxidation (when the oxide scale thickness does not exceed a few microns) the barrier scale for cation and anion counter diffusion structure (architecture) will be developed. This finally will lead to the formation of slow growing and adherent (due to

the alloying with RE elements) TBC which protects metal matrix against a high temperature corrosion. Figure 3a corresponds to the transformation of Beilby layer into the oxide layer which is a mixture of nanocrystallites of all element oxides composing the alloy, during the first oxidation minutes at $1200^{O}C$. The following schemes (Figures 3b and 3c) illustrate a possibility of the continuous formation of the TGO out of Al_2O_3 on the investigated alloy in spite of the low Al content (<5%) in it. These figures also demonstrate a mechanism of the self-organized TBC with the self healing potential on the alloy surface at high temperatures. The reservoir under TBC supplies Al (as well as Cr) atoms required for the reproduction of the healing agents on the crack surfaces (in case of their appearance in the coating) in the form of Al_2O_3 particles (as well as of Cr_2O_3, partially). The formation of TBC on the Fe-45%Cr-5%Al-0.3%La alloy will allow creating a metal/metal/ceramics composition with a functionally distributed sandwich architecture characterized with the self healing features similar to that of the wound on the skin. Here it is given the schematic of the structure (architecture) on the substrate which is placed together with the cross section of the skin.

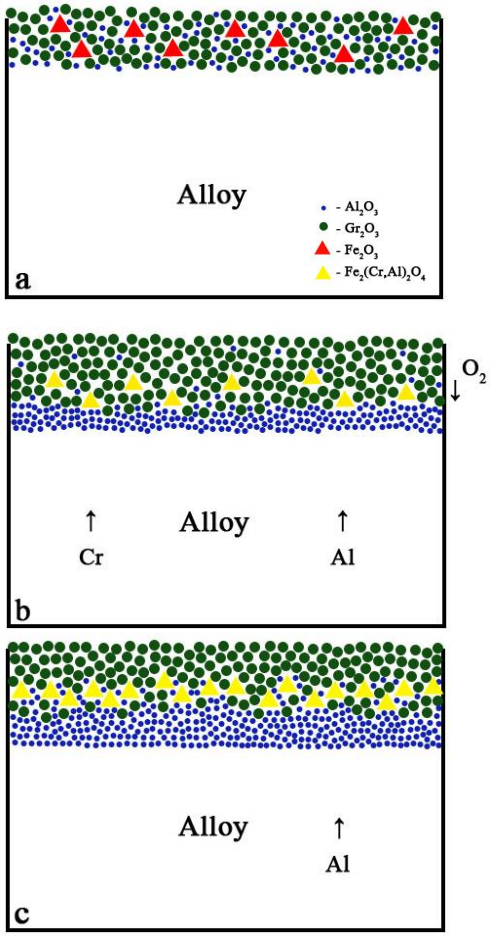

Figure 3. Synergistic effects of high chromium content on the formation of Al_2O_3 TGO scales during the transient oxidation of Fe-45%Cr-5%Al-0.3%La alloy at $1200^{0}C$ after (a) 10 min, (b) 1hr and (c) 10hrs.

Objective #3: Contribute to strengthen New Mexico aerospace engineering educational and research programs at New Mexico State University (NMSU) and New Mexico Institute of Mining and Technology (NMT) and use the aerospace programs to interest New Mexico K-12 students in the Science Technology Engineering Math (STEM) disciplines.

Accomplishments on Objective #3:
In December, 2009 NMSU proposals for MS and PhD degrees in Aerospace Engineering were approved by the New Mexico State Board of Finance, the final step in the approval process. These graduate degrees were effective Fall, 2011. In making the case for these graduate programs the NASA EPSCoR project was cited as an example of aerospace research currently ongoing at NMSU and as an example of the type of research that will be done in the future by students in the MSAE and PhD AE programs. These graduate AE programs at NMSU involve a three-way distance education collaboration among New Mexico State University, New Mexico Institute of Mining and Technology, and the University of New Mexico in the delivery of aerospace and related courses. The NMSU AE graduate programs will be essential in enabling us to attain national competitiveness for research and scholarly activity.

Objective #4: Develop nationally competitive research expertise and research programs in the proposed and related areas in preparation for obtaining follow-up research funding.

Accomplishments on Objective #4: The research group has been active in publishing research results in quality journals and at technical conferences – 37 journal papers and 35 conference papers/presentations reflecting results obtained in the framework of the project have been published. Special issue of International Journal of Engineering Science - one of the leading interdisciplinary engineering journals in the world – "Structural Health Monitoring in the Light of Inverse Problems in Mechanics" has been prepared by PIs of the project (*Intl. J. Engineering Science*, **48**(10), 2010). Seventeen proposals in the same or relevant technical areas have been submitted, and several of these have been funded. Thus we have demonstrated significant research accomplishment and good success in securing follow-on funding to support research in SHM and related areas.

Objective #5: Develop collaborations with key entities in New Mexico, Los Alamos National Laboratory (LANL), Sandia National Laboratories and with relevant NASA Centers, enhancing the prospects for future nationally competitive research.

Progress on Objective #5: The collaboration with Los Alamos National Laboratory (LANL) which led to a funded project in health monitoring during Years 1 and 2 has progressed well. The LANL collaborators bring their extensive experience in sensing and hardware applicable to health monitoring to complement the theoretical work being done by the NMSU group. This marriage of real-world and theoretical research has been of direct benefit to the NASA EPSCoR research project. One of the NMSU graduate students (Krystal Deines) funded by this EPSCoR project participated in the NSF sponsored Summer Dynamics School run by LANL during the summer of 2010; Ms. Deines worked on a student research team conducting health monitoring studies of wind turbine blades.

Research success of individual investigators as measured by:

Special Journal Issues Published

Burton, T., Hynes, P. and Sevostianov, editors, Special Issue: Structural Health Monitoring in the Light of Inverse Problems in Mechanics, *Intl. J. Engineering Science*, **48**(10) (2010)

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33. Kruse, W., and Zagrai, A.N. Investigation of Linear and Nonlinear Electromechanical Impedance Techniques for Detection of Fatigue Damage in Aerospace Materials," Proceedings of 7th International Workshop of Structural Health Monitoring, 9-11 September 2009, Stanford University, California, pp.1840-1847.
34. Torkamani, S., Butcher, E. A., Todd, M. D., and Park, G., Damage Assessment using Hyperchaotic Excitation and Nonlinear Prediction Error, 8th International Workshop on Structural Health Monitoring, Sep. 13-15, 2011, Stanford, CA.
35. Sari, M. and Butcher, E. A., Three Dimensional Analysis of Rectangular Plates with Undamaged and Damaged Boundaries by the Spectral Collocation Method, proceedings of 8th International Conference on Multibody Systems, Nonlinear Dynamics, and Control, ASME IDETC'11, Washington, D. C., Aug. 28-31, 2011.

Follow-on grant proposals submitted/funded

1. Co-PI: Sayavur Bakhtiyarov "A Model for Participatory, Collaborative STEM Learning", CCRAA Grant with Amarillo College, TX, Department of Education Total: $3,242,767; NMT: 1,498,709; Mechanical Engineering Department at NMT: $487,000 (submitted and awarded)
2. PI: Sayavur Bakhtiyarov NASA "Center for Intelligent and Self-Repairing Aerospace Structures", MUREP Group 5 University Research Centers Program. Joint proposal with NMSU, UNM, NMT, NNMC, LANL and SNL. $5,000,000 for 5 years, September 1, 2009 – August 31, 2014 (submitted and not awarded).
3. PI: Eric Butcher "An Integrated Framework for Order Reduction, Robust Control and Real-Time Dynamic Substructuring of Nonlinear Multi-Scale Hybrid Aerospace Systems", DOD $513,385 May 8, 2009 – May 7, 2012 (submitted and awarded).
4. PI: Thomas Burton, Eric Butcher, Igor Sevostianov "Development of a novel methodology for the health monitoring and self-healing of structural elements and joints", LANL (submitted and awarded).
5. PI: Thomas Burton "Center for Modeling, Sumulation, and Validation (MSV) in the Aerospace Science", NASA Group 4 URC, $5,000,000 (submitted and not awarded).
6. PI: Andrei Zagrai "Embedded Ultrasonics for Structural Monitoring of Space Applications", AFRL, Kirtland AFB, $199,999 for four years (submitted and awarded).

7. PI: Andrei Zagrai "Ultrasonic Assessment of Microstructure in Aerospace Materials", WP AFRL, $25,000 student funding for one year (submitted and not awarded).
8. PI: Andrei Zagrai "Intelligent Structural System for National Security Applications", Los Alamos National Laboratories (LANL), $100,000 for one year (submitted and not awarded).
9. PI: Sayavur Bakhtiyarov "Design and Development of Modified Spiral Orbital Tribometer (MSOT) and Tribological Properties Measurements on High Temperature Ionic Lubricants", DoD AFRL, Air Force Defense Research Sciences Program, Small University Grants ($50,000 for 1 year)
10. PI: Andrei Zagrai, "Structural Integrity Assessment using Piezoelectric and Magneto-Elastic Active Sensors," DOD ARL, $309,973 (submitted and not awarded)
11. PI: Andrei Zagrai, "Focused Learning Strategy for Improving Competitiveness of STEM Students with Disabilities," NSF RDE, $164,082. (submitted and not awarded).
12. PI: Andrei Zagrai, "A Scanning Laser Doppler Vibrometer for Space Systems Research and Aerospace Education," DOD DURIP, $330,850 (submitted and not awarded).
13. PI: Igor Sevostianov, "Multiscale materials characterization for modeling of multiphysics processes in heterogeneous materials with hierarchical structure", DOE, (submitted and not awarded).
14. PI: Igor Sevostianov, "Cross-property connections for microcracked materials: assessment of strength reduction from the measurements of electrical resistance", NSF, , (submitted and not awarded).
15. PI: Igor Sevostianov, "Assessment of strength reduction due to accumulated damage in fatigued materials using cross-property connections", NASA-space grant consortium, (submitted and awarded).
16. PI: Igor Sevostianov, "Advancement of micromechanical criteria for fracture toughness", NASA-space grant consortium, (submitted and not awarded).
17. PI: Igor Sevostianov, "Assessment of mechanical performance of radiation-damaged materials by means of electric conductivities." (pre-proposal submitted)

Improvements in jurisdiction research and development infrastructure

- NMSU: Development of an experimental facility for vibration based health monitoring has been completed and is now operational. We have also initiated development of a fatigue testing facility that will enable experimental study of distributed micro-damage. The new experimental facilities will significantly improve NMSU's capabilities in SHM and DP.

Systemic change as evidenced by:

- Reordered jurisdiction and/or institutional priorities: An NMSU federal initiative based on this collaboration was a priority earmark item for FY 2010.
- Increased financial commitment from the jurisdiction, industry, and participating institutions: This research program was successful in receiving 100% matching funds from the participating institutions and State of New Mexico. This was a significant financial commitment by NMSU.

Examples of successful transfer of technology to the private sector:

- Self-Healing Materials Workshop**,** BOEING, Seattle, WA, January 20-21, 2009.
- Dr. Butcher and PhD student M. Shudeifat have collaborated with Management Sciences, Inc. in Albuquerque to develop a new SHM approach for damaged rotating shafts.

Extent to which collaborations with jurisdiction agencies, industry, research and academic institutions and with NASA have evolved:

- Dr. Butcher and PhD student M. Shudeifat have collaborated with Management Sciences, Inc. in Albuquerque to develop a new SHM approach for damaged rotating shafts.
- The opportunity that Krystal Deies had to spend the summer in the Los Alamos Summer Dynamics School was enabled by her experience working in the NASA EPSCoR program and enhanced the already close collaboration in SHM research with LANL.
- NMSU was awarded the FAA COE for Commercial Space Transportation (Dr. Hynes is the PI) as leader in a coalition of a number of universities. Research collaboration with the University of Central Florida has been initiated recently in structural health monitoring as part of this project.
- In the area of nonlinear ultrasonics, NMT researchers have been interacting with Dr. George Baaklini, Director of Optical Instrumentation & NDE Branch at NASA Glenn Center.
- To better fit within the branch research mission, for this project Dr. Baaklini recommended close collaboration with Dr. John Lekki – an expert in integrated vehicle monitoring. Interaction with Dr. Lekki has led to the concept of the future collaboration in which the proposed SHM methodologies will complement existing NASA Glenn efforts in SHM of aerospace systems.
- Dr. John Lekki, Optical Systems Research Engine, NASA Glenn Research Center

Evidence of how EPSCoR activities have furthered jurisdiction priorities: Structural health monitoring and damage prognosis are now recognized as important research areas in the NMSU College of Engineering.

Dissertations and Theses:

- Kramer, M. MS Thesis, New Mexico State University (2009).
- Al-Shudeifat, M., PhD Dissertation, New Mexico State University (2010).
- Dominguez, D., MS Thesis, New Mexico State University (2010).
- Picazo, M., MS Thesis, New Mexico State University (2010).
- Ervin, J. MS Thesis, New Mexico State University (2010).
- Bakhtiyarov, A. MS Thesis, New Mexico Tech (2010).
- Sari, M., PhD Dissertation, New Mexico State University (2011).
- Mercer, J. MS Thesis, New Mexico State University (2011).
- Deines, K. MS Thesis, New Mexico State University (2011).
- Kruse, W. MS Thesis, New Mexico Tech (2011).
- Gigineishvili, V. MS Thesis, New Mexico Tech (2011).

Demographic (ethnicity/race and gender through self identification) information on participants:

- Faculty – including names and institutions
  - Sayavur Bakhtiyarov (New Mexico Institute of Mining and Technology) – white/male
  - Andrei Zagrai (New Mexico Institute of Mining and Technology) – white/male
  - Thomas Burton (New Mexico State University) – white/male
  - Igor Sevostianov (New Mexico State University) – white/male
  - Eric Butcher (New Mexico State University) – white/male
- Post-doctoral researchers, graduate, and undergraduate students
  - Ma'en Sari (PhD student funded by NMSU cost sharing) – white/male
  - Mohammed Al-Shudeifat (PhD student funded by NMSU cost sharing) - white/male
  - Shahab Torkamani (PhD student funded through NMSU Graduate Research Enhancement Grant and LANL MOU grant) – white/male
  - Ivan Argatov (postdoctoral 2009 funded by Los Alamos MOI grant) – white/male
  - Vladimir Kusch (postdoctoral researcher) - white/male
  - Morad Nazari (PhD student funded by NMSU cost sharing) – white/male
  - Joshua Mendoza (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/male
  - Christopher White (BS undergraduate student funded by NASA EPSCoR grant) – white/male, student registered with the disability services.
  - Julie Mercer (MS graduate student funded by NASA EPSCoR grant) – white/female
  - Krystal Deines (MS graduate student funded by NASA EPSCoR grant) – white/female
  - Mario Picazo (MS graduate student funded by NASA ESPSCoR grant)-Hispanic/male
  - David Dominguez (MS graduate student funded by Nasa EPSCoR grant-Hispanic/male
  - Akshin Bakhtiyarov (MS graduate student funded by NASA EPSCoR grant) – white/male
  - Erica Summers (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/female
  - Dunte Hector (BS undergraduate student funded by NASA EPSCoR grant) – Black/male
  - Anais Linan (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/female
  - Marcus Cramer (MS graduate student funded by NASA EPSCoR grant) – white/male
  - Walter Kruse (MS graduate student funded by NASA EPSCoR grant) - white/male
  - Vlasi Gigineishvili (MS graduate student supported by local funds and has volunteered for some work on the project; however was not supported by NASA EPSCoR; he is not a US citizen) – white/male