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LLNL-TR-737827

Mosaic Transparent Armor System Final Report CRADA No. TC02162.0

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August 31, 2017

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Mosaic Transparent Armor System

Final Report
CRADA No. TC02162.0
Date Technical Work Ended: May 20, 2013

Date: July 10, 2013 Revision: 1

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and The Protective Group, Inc.

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B. Project Scope

This was a collaborative effort between Lawrence Livermore National Security, LLC as manager and operator of Lawrence Livermore National Laboratory (LLNL) and The Protective Group, Inc. (TPG) to improve the performance of the mosaic transparent armor system (MTAS) for transparent armor applications, military and civilian.

LLNL was to provide the unique MTAS technology and designs to TPG for innovative construction and ballistic testing of improvements needed for current and near future application of the armor windows on vehicles and aircraft.

The goal of the project was to advance the technology of MTAS to the point that these mosaic transparent windows would be introduced and commercially manufactured for military vehicles and aircraft. The replacement of laminated transparent armor (LTA) with MTAS would improve

ballistic performance through higher ballistic resistance at reduced weights, improve multi-hit capability, improve visibility after initial impacts from projectiles and debris, and reduce fabrication costs for ceramic components.

This CRADA was originally designated as an eleven (11) month project consisting of four major tasks and the following deliverables:

Task 1.1 Deliver report on polymer selections to TPG	(Month 1.5) LLNL
Task 1.2 Deliver coupons to LLNL for tests	(Month 2) TPG
Task 1.3 Deliver report to TPG with data from coupon testing	(Month 2) LLNL
Task 1.4 Deliver report to LLNL for ballistic tests for 4 cell targets	(Month 3 TPG
Task 2.1 Deliver report on scale-up of sol-gel process to TPG	(Month 4) LLNL
Task 2.2 Deliver report to LLNL with for ballistic tests with spinel tiles	(Month 5) TPG
Task 3.1 Deliver target design to TPG for oblique ballistic tests	(Month 6) LLNL
Task 3.2 Deliver report to LLNL for oblique ballistic test results	(Month 7) TPG
Task 4.1 Deliver coupons to LLNL made with final polymer selection(s)	(Month 3.5) TPG
Task 4.2 Deliver report to TPG regarding polymer coupon test results -	(Month 8) LLNL
Task 4.3 Deliver report to LLNL for ballistic test of targets using polymer	(Month 9)TPG
Task 4.4 Deliver report to TPG for special design for windshield targets	(Month 9) LLNL
Task 4.5 Deliver report to LLNL for ballistic test of windshield targets-	(Month 9) TPG
Task 4.6 Write Final report	(Month 12) LLNL/TPG

Final Report and Abstract due within thirty (30) days of completion or termination of the project, as required under Article XI of the CRADA. (LLNL/TPG)

A no-cost time extension request (NCTE), executed on April 27, 2012, extended the CRADA for an additional six months, through November 20, 2012, to allow the company enough time to resolve financial concerns or to negotiate an amendment to re-evaluate the scope and deliverable timelines. A second NCTE, executed on November 15, 2012, extended the CRADA for another additional six months, through May 20, 2013, to allow the company more time to resolve financial concerns or to negotiate an amendment to re-evaluate the scope and deliverable timelines.

The initial deliverables associated with Tasks #1 and #2 were successfully completed. The remaining deliverables were not completed due to funding limitations of TPG.

C. Technical Accomplishments

This section of the report details specific technical accomplishments of LLNL contributions toward the LLNL-TPG CRADA, TC02162, through May 20, 2013. Efforts include development of spinel processing and polymer seam development. The spinel portion includes both sol-gel production of spinel powders and transparent ceramic consolidation. The polymer seam

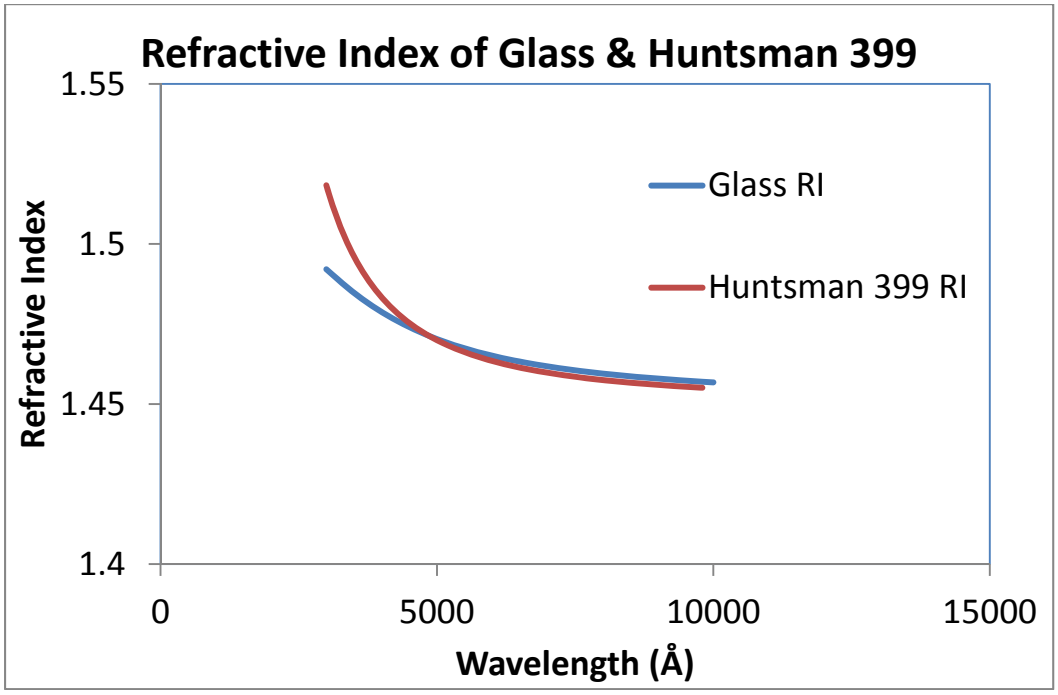
development includes testing of commercially available polymers and in-house synthesis of high index clear polymers.

Spinel (sol-gel preparation): The LLNL technique for sol-gel production of spinel powder is essentially a single pot synthesis. Nitrate salts of magnesium and aluminum are dissolved in ethanol and stirred in a sealed reaction vessel. Gaseous ammonia is flowed over the service of the liquid and the pH of the solution is uniformly raised to the precipitation point of the mixed hydroxides. Once precipitation is completed the resulting suspension is washed and calcined to produce pure spinel nanopowder.

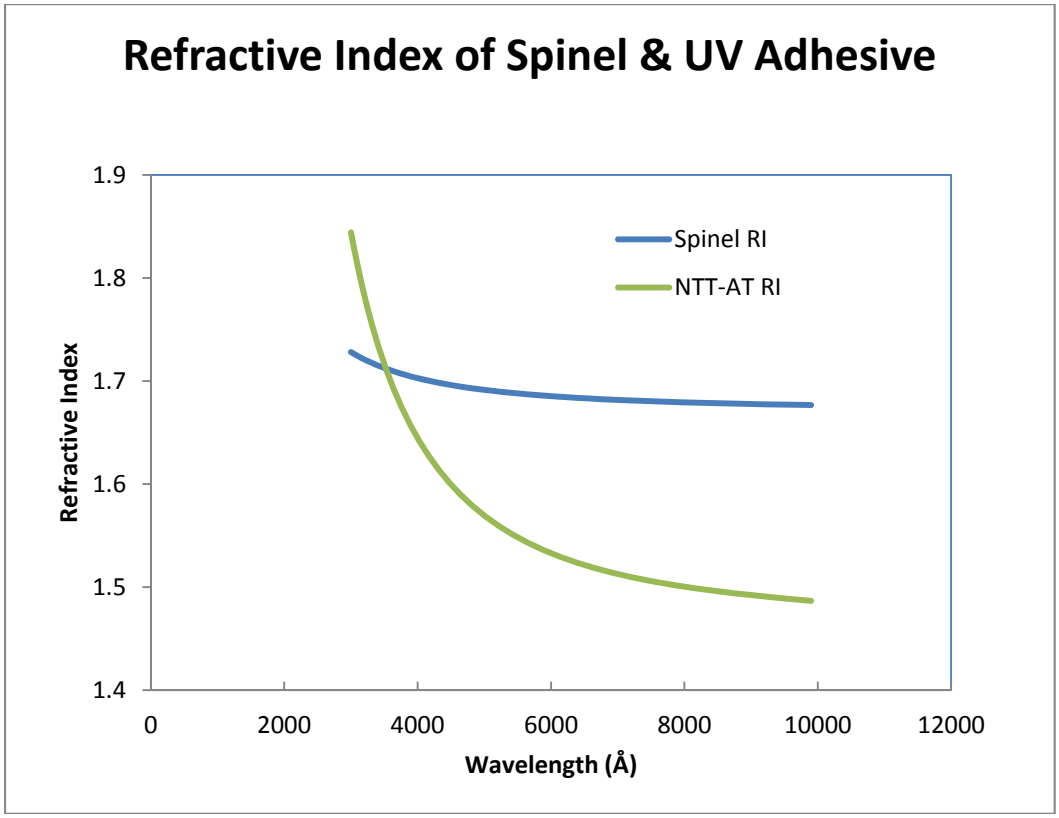
Recent sol-gel development has focused on finding a commercial partner for production of spinel ceramic tiles. To this end Nanocerox, Inc. was approached and is currently in the first phase of production of transparent ceramic spinel test pieces. In December 2012, Joshua Kuntz traveled to Nanocerox, in Ann Arbor, MI, to teach the sol-gel production technique and discuss potential consolidation routes. Additionally, LLNL has shipped LLNL produced spinel powder to Nanocerox to accelerate the ceramic fabrication side of the project.

Spinel (ceramic processing): Sol-gel produced spinel powder has been consolidated into transparent ceramics through a processing plan consisting of calcination, LiF addition, spray drying, hot-pressing, and hot-isostatic pressing (HIP'ing). To produce spinel parts in a scalable and cost effective manner, recent efforts have focused on development of processing conditions to enable replacement of hot-pressing with vacuum or oxygen sintering. To date, samples have not yet reached high enough density to allow for can free HIP'ing. It has been shown that LiF additions, while key to hot-pressing, only hinder pressureless sintering methods. Also, nearly identical densities can be reached by oxygen sintering compared to vacuum sintering. Ongoing efforts are focusing on increasing the as-sintered density.

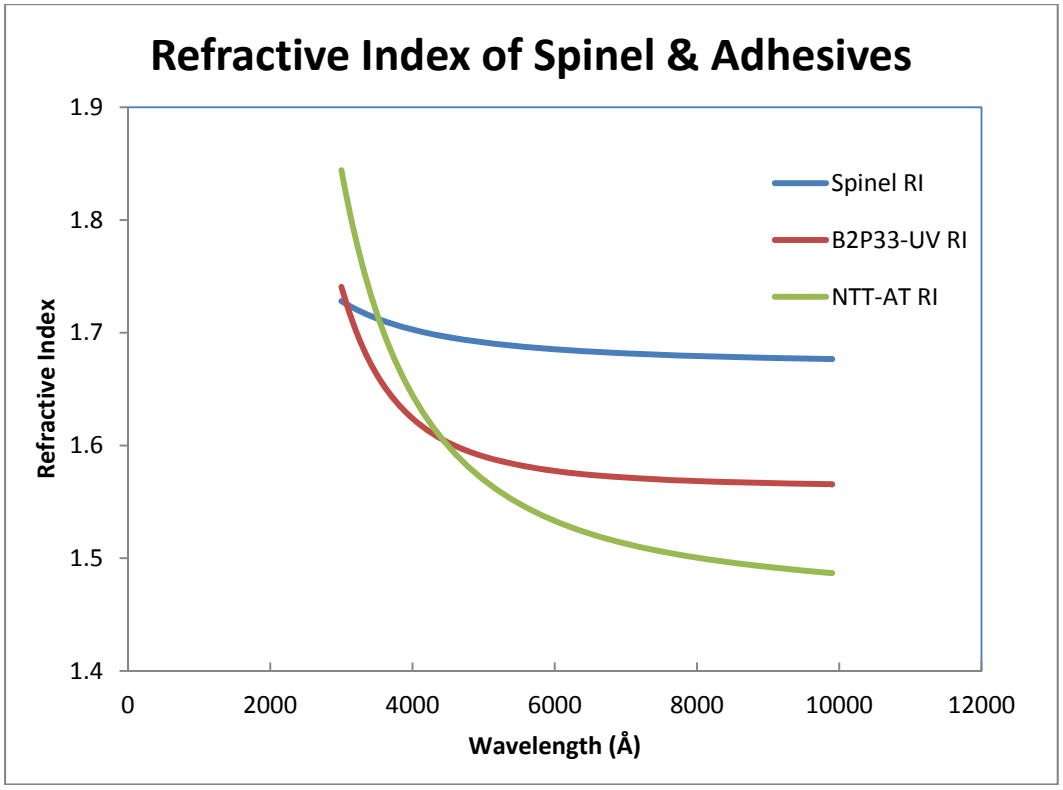
Polymer seams (commercial): One of the particular challenges to production of Mosaic Transparent Armor System (MTAS) is the reduction of the visible impact of the polymer seams between glass or ceramic cells. To perform in MTAS the polymers must have several key properties: mechanical and optical. The optical properties of note include being colorless in the visible and having an index of refraction that matches the adjacent glass or ceramic cells. Huntsman 399 has been identified as an adequate commercial polymer for glass to glass bonds. While Huntsman 399 has reasonable visibility there still remains significant optical distortion at the polymer glass bond. To get an understanding of the cause of this distortion the index of refraction of glass samples and the polymer were measured. The curves can be seen below. While the index matches at ~470nm, at the lower end of the visible spectrum the index can be off as much as 0.005.



For seams between ceramic cells the challenge becomes greater. While many companies claim to sell transparent colorless polymers with high index, most fail to meet those criteria. Most polymer samples were so colored as to make them useless for windows, while others did not obtain the specified index. Critical values of index of refraction for ceramic to ceramic seams are ~1.68 for spinel and ~1.75 for sapphire. The values are approximate since the values are strongly dependent on wave length. Recently, LLNL has identified a supplier of high index polymers with promise, NTT Advanced Technology Corp. (NTT-AT). While still in the development stage a sample of their UV curable polymer resulted in the plot below. While the curve is very steep, there is at least a crossover point at 355nm, just outside the visible. Additional materials, with higher index, have been requested.



Polymer seams (LLNL synthesized): To have greater control over the polymer development process, and to accelerate the production of index matching polymers for ceramic to ceramic seams, LLNL has added a polymer chemist to the project, Jeremy Lenhardt. In the short time he has been working on the project, he has already demonstrated polymers with higher index over the visible spectrum than any commercially available polymer system. Initial materials systems are sulfur containing acrylate monomers with UV or heat activated initiators. The resulting index plot of such a system can be seen below, with the commercial polymer from NTT-AT for comparison. While the low wavelength index is not quite as high as the NTT-AT material, for most of the visible spectrum the index match is better. There is still compositional room in the phase stability of this polymer system to increase the index and efforts are ongoing in this area. Another benefit of these compounds is the improved slope of the index indicating a potential for index matching over a broad index range.



D. Expected Economic Impact

The Execution of this CRADA has enabled TPG to produce MTAS at the prototype scale. If implemented by the DoD, these could result in significant cost saving to the Nation.

D.1 Specific Benefits

Benefits to DOE

This CRADA benefits DOE and government agencies by the technical transfer of LLNL technologies into military and civil applications from recent research and development projects funded through government projects. If commercialized, implementation of MTAS technology would have resulted in significant licensing opportunities for LLNL.

Benefits to Industry

The taxpayer and industry benefits from the transfer of technologies from government funded projects to new materials and armor designs that protect the soldiers now in combat as well as law enforcement that protect the taxpayer. LLNL was to provide the unique MTAS technology and designs to TPG for innovative construction and ballistic testing of improvements needed for current and near future application of the armor windows on vehicles and aircraft. Had this CRADA been successfully completed, the licensing of the technology could have resulted in

production business to TPG through orders from the military and private companies dealing with armor for vehicles and aircraft.

E. Participant Contribution

The execution of this CRADA has enabled TPG to produce MTAS at the prototype scale. If implemented by the Department of Defense (DoD), these could result in significant cost saving to the Nation. No new inventions were developed during this CRADA.

F. Documents/Reference List

Reports
There were no published reports. All reports were internal to the project.

Copyright Activity
None

Subject Inventions
None

Background Intellectual Property

LLNL disclosed the following Background Intellectual Property (BIP) for this project:

U.S. Patent Application No. 12/107277– *Mosaic Transparent Armor*; Inventors: Richard Lee Landingham, Steve J. Deteresa, John Hunter (IL11732) [Patent Abandoned]

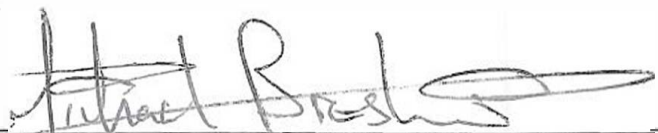
TPG decided not to pursue a license for the above LLNL BIP.

TPG did not disclose any Background Intellectual Property for this project.

G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.



23 JAN 2014

Michael Breslin, VP New Program Development — Date
The Protective Group, Inc.

3/27/2014

Joshua D. Kuntz, LLNL Principal Investigator — Date
Lawrence Livermore National Laboratory

28 March 2014

Richard A. Rankin, Director, Industrial Partnerships — Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

Mosaic Transparent Armor System

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B. Purpose and Description

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The project was not completed on time, two no-cost time extensions were executed. Additionally, the project was not fully funded, due to funding limitations of TPG.

C. Benefit to Industry

The taxpayer and industry benefits from the transfer of technologies from government funded projects to new materials and armor designs that protect the soldiers now in combat as well as law enforcement that protect the taxpayer. LLNL was to provide the unique MTAS technology and designs to TPG for innovative construction and ballistic testing of improvements needed for current and near future application of the armor windows on vehicles and aircraft. Had this CRADA been successfully completed, the licensing of the technology could have resulted in production business to TPG through orders from the military and private companies dealing with armor for vehicles and aircraft.

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E. Project Dates

June 20, 2011 through May 20, 2013