Industrial Additive Manufacturing Workshop on

METALS AND CERAMICS

Brookhaven National Laboratory

Workshop, April 25, 2019

ORGANIZING COMMITTEE:

Jun Wang, Brookhaven National Laboratory-
Energy and Photon Sciences

Alessandra Colli, Brookhaven National Laboratory-
Interdisciplinary Science Department

Shomeek Mukhopadhyay (Obsidian)

Brookhaven National Laboratory
Upton, NY 11973

BROOKHAVEN NATIONAL LABORATORY

CIEES CENTER FOR INTEGRATED ELECTRIC ENERGY SYSTEMS AT STONY BROOK UNIVERSITY

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1. Executive Summary and Recommendations

With the goal of accelerating the development of the additive manufacturing (AM) and supporting industry in this field, Brookhaven National Laboratory (BNL) brought together additive manufacturing industry, academia, and representation from the Department of Energy (DOE) for a one-day workshop on April 25, 2019 to provide a forum to learn about the unique capabilities in BNL, pursue potential collaborative partnerships, and develop strategies for the AM industry to be better engaged with BNL.

In summarizing all discussions from the full workshop day including presentations, questions and answers, as well as breakout session discussions, a number of key recommendations are described in the following. The organizing committee believes the recommendations and suggestions will help the growth of the AM community and BNL to fine tune the future strategic planning in the AM field.

Recommendation 1: Build a dedicated business model to work with industry. There are known incompatibilities between the metric of success of the user's facilities and the needs of the industry, indicating that a synergy and coordination needs to be reached between cutting-edge research in AM and high-throughput capabilities. Feasibility tests with a specific target should be developed in partnership with the industry, to improve their understanding of the capabilities of the synchrotron-based technique, while looking at moving toward a large-scale experiment. Bringing industrial partners to the synchrotron with an initial test or demonstration experiment will help them gain knowledge of relevant techniques, while bridging the gap between applied industry and basic science research. It is important that there is awareness from scientists and national labs about problems in real-world applications, developing a connectivity that will grow the knowledge and the capabilities of the additive manufacturing community.

The committee suggests that this recommendation be incorporated with the directorate industrial research program. The industrial research office should work with the user facilities to implement a business model to work with industry to meet industry needs. A summer school to bring the knowledge of capabilities to industry could be a good start.

Recommendation 2: Build a database for modeling validation. On the path to validate methods for quality and failure analysis in additive manufacturing, large quantities of data must be examined to build a consistent database of reference data that is critically needed for modeling validation. Currently, the modeling effort in additive manufacturing is huge and widespread, however there exists a large variability among diffe*rent* models, thus, it is important to understand which one is relevant and pertinent to a specific purpose. The characteristics of the 3D printed components are often not consistent across the different parts, for example, stress-strain variates locally according to the design features of each printed part. Models should be developed along with benchmark measurements and quantitative measurements to obtain valid results and be truthful with the actual characteristics of the materials and design of each part.

The committee suggests that this recommendation be considered in the development of the new high x-ray energy engineering beamline (HEX) and other related beamlines. The capabilities like high-throughput should be taken into account in the design of the beamline, as well as infrastructure for data mining.

Recommendation 3: Build partnership with other institutions. It is important to work with other organizations to develop a well-defined workflow for standardization and metrology. Partnering with other institutions will better leverage resources and complementary capabilities to enhance R&D in AM and to address scientific and technical challenges which are faced by the AM community.

The committee suggests that this recommendation be considered in directorate strategic planning to pursue potential collaborative partnerships with other institutions. Dedicated efforts should be made to reach out to potential partners. Targeted conferences, collaborations, joint proposals could be ways to make connections and build potential partnership.

2. Workshop Introduction

A workshop on "Industrial Additive Manufacturing on Metals and Ceramics", sponsored by Center for Integrated Electric Energy Systems (CIEES) at Stony Brook University (SBU), was held at Brookhaven National Laboratory (BNL) on April 25, 2019. The workshop brought together about 60 invitees from industries including big and small/startup companies, academia, government, and participants from BNL for this one-day workshop.

Jim Misewich, BNL's Associate Lab Director for Energy and Photon Sciences Directorate, welcomed the attendees, discussed overall goals and summarized the strategic direction of Additive Manufacturing (AM) research in BNL. Manny Oliver, Director of the SBIR/STTR Program Office, Department of Energy (DOE), introduced the SBIR/STTR program and the related procedures of funding applications. Qun Shen, Deputy Director for Science for National Synchrotron Light Source-II (NSLS-II) at BNL, provided an overview of NSLS-II capabilities and thoughts for AM research using NSLS-II and other BNL facilities and capabilities. Eric Dooryhee, Program Manager of Diffraction and In-Situ Scattering Beamlines at NSLS-II followed with a discussion focusing on a new high energy x-ray diffraction and imaging beamline and its capabilities. A representative from Empire State Development's Division of Science, Christopher Rooney, introduced the AM ecosystem in New York state, stressing on key achievements and the importance of collaborations between education, research and industry.

During the morning session, speakers Shawn Kelly (Oerlikon), Michael Hollenbeck (Optisys), Vipul Gupta (GE), representing both large industry and small/start-up companies, provided the R&D and applications overview from the industrial perspective. Collaborators and partners Lyle Levine (NIST), Dan Lewis (RPI), and Adam Brooks (EWI, representing ASTM International) discussed AM activities and research as well as the latest developments in AM standardization.

After a poster session during a working lunch, participants were invited to join round table discussions organizing by area of interest. The organizers pre-selected four topics: 1) technical challenges in AM community 2) X-ray techniques and their application 3) emergent applications in AM and 4) partnering agreements with BNL. The round table discussions were facilitated, respectively, by Eric Dooryhee (NSLS-II, BNL), Juergen Thieme (NSLS-II, BNL), Shomeek Mukhopadhyay (Obsidian), and Erick Hunt (BNL). Additionally, Manny Oliver (DOE) held a one-on-one discussion with attendees who were interested in funding information and policies involving SBIR/STTR projects. A NSLS-II tour, led by NSLS-II scientists Eric Dooryhee, Milinda Abeykoon, Michael Drakopoulos, Zhong Zhong, and Jun Wang, was provided at the end of the workshop (see Appendix 1 for the complete workshop agenda).

The organizers would like to thank the workshop sponsor CIEES at Stony Brook University, all attendees, the speakers, the staff at BNL who assisted with the workshop preparation especially Linda Hanlon, Lana Belyavina, Diana Murphy, and Elspeth McSweeney. Special thanks go to Michael Cowell and Jim Misewich for their guidance and support.

3. Workshop Description

The Industrial Additive Manufacturing Workshop on Metals and Ceramics had been conceived and planned in the context of the Metal Additive Manufacturing Strategy of BNL. The strategy (see Figure 1) aims at combining techniques which provide multi-length scale information on statistically relevant ensembles with data analytics to correlate specific structural defects with failure probability. Ultimately, the approach allows establishing a database of reference information to verify and validate 3D printed structures and materials for superior performance and extended durability.

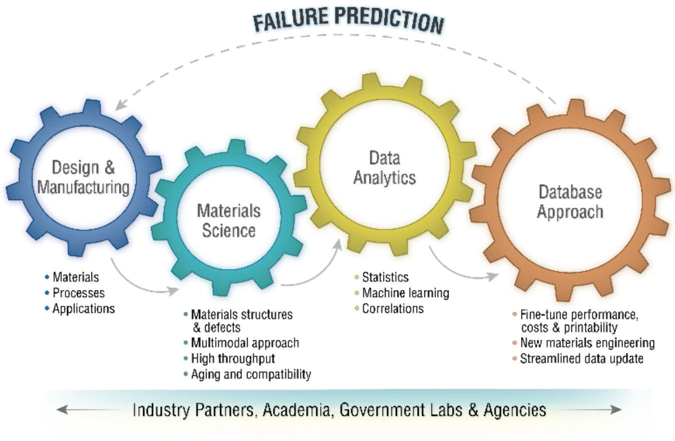

Figure 1. Brookhaven Lab Metal Additive Manufacturing strategy concept.

The strategy is pursued for both structural and functional Additive Manufacturing (AM) components. The structural thrust focuses on the integrity of high-reliability applications, such as civil aviation; it has a strong connection to testing for compliance with existing norms and standards, while it also helps to define new rules and documentation. The functional thrust looks into innovative 3-D printing capabilities that will provide high-performance components that require high-precision printing. This thrust can include research correlated to defense applications and new technologies, as well as identifying new materials for quantum information science (QIS) and metamaterials. One of the strategic values of some high-precision high-yield printing techniques, is the capability to combine different materials within the same printing procedure, making the 3D printing method very versatile and capable to address special needs.

With this background in mind, the Workshop had been designed to specifically address the following aspects:

1. Introduce Brookhaven Lab as a partner in developing reliable and high-performing Additive Manufacturing processes and components.
2. Provide a platform to develop a business model for efficient integration of characterization tools, data analytics and databases.
    i. Introduce material analysis tools and correlate them with specific industry problems.
    ii. Coordinate data analytics tools to build a base for reliability prediction.
    iii. Introduce, discuss and develop a business model for a database approach in reliability predictions.
    iv. Allow networking with the Additive Manufacturing industry to identify partners and collaborations.
    v. Define pilot projects to address specific material issues and help the industry to estimate required resources and validate the techniques in relation to their questions.
3. Discuss funding mechanisms and accessibility to BNL user facilities for industry.
4. Prepare a summary report that identifies the specific needs of the Additive Manufacturing industry and tune the BNL strategy accordingly.

The workshop brought together industry, agencies and government to discuss the issues in metal and ceramic AM. The event highlighted one very important aspect of the Brookhaven Lab Additive Manufacturing Strategy: the connection with the onsite user's facilities for material analysis research, in particular with the NSLS II.

4. Round Table Discussions

The breakout session in the afternoon was primarily focused on giving the attendees the opportunity to interact, brainstorm and discuss with each other over relevant technical issues affecting AM and logistical aspects of working directly with Brookhaven Lab. The participants at each table mainly represented the industrial sector, with presence also from academia and government agencies.

The summary of each discussion table is reported in the next Sections 4.1 to 4.4.

4.1. Table 1: Diffraction / Scattering

Moderator: Eric Dooryhee, Brookhaven National Laboratory

1) Validation of existing models: the modeling effort in additive manufacturing is huge and widespread, however there is a large variability among different models; thus, it is important to understand which one is relevant and pertinent to a specific purpose. The characteristics of the 3D printed components are often not consistent across the different parts; for example, stress-strain variates locally according to the design features of each printed part. Models should be developed along with benchmark measurements and quantitative measurements to obtain valid results and be truthful with the actual characteristics of the materials and design of each part.
2) Understanding the as-built microstructure and properties for the development of predictive tools and models: the properties of 3D printed components massively change during the postprocessing phase; this phase may include the use of heat treatments, chemical etching, and induction methods. The postprocessing activities introduce changes in phase development, presence of precipitates, residual stress, porosity. In situ, time-resolved investigation during postprocessing can help to better understand the evolution of the additively manufactured material. Among the techniques that could be valuable in this context, USAXS/SAXS/WAXS could help to optimize the postprocessing activities.
3) Focus of investigation: most studies investigate the melting pool during the printing process, however very little is known about what happens in the surrounding regions. The investigation should be directed away from the melting pool as well as below it, where pressure waves, vaporization, and different cooling rates may create a relevant impact within the material. It is important to look at different layers and different time scales within the frame of the printing process. Diffraction may be introduced to help investigate changes over adjacent printed layers and provide a measure for residual stress as a function of depth (e.g. due to the temperature gradient): the application can start from 15 to 100 micrometers and upscale to penetrate a cubic centimeter of volume with a rastered beam. The nature of the materials printed via additive manufacturing can however complicate measurements as the local structure variates. The 3D printed material is not a single crystal and can show anisotropy and variations in the grain size that may complicate the measurement process.
4) Business model: there are known incompatibilities between the metric of success of the user's facilities and the needs of the industry, indicating that a synergy and coordination needs to be reached between cutting-edge research and high-throughput capabilities.

Suggestions highlighted during the roundtable discussion are the following:

1) Some benchtop and laboratory procedures could be imported to the beamline to help dramatically improve the knowledge while introducing in-situ experiments.
2) The access to the user facilities for the additive manufacturing industry should be guided by the relevance of certain questions to the community and should be prioritized by technical challenges that are most relevant to the larger community. In this context, it is important that there is awareness from scientists and national labs about problems in real-world applications, developing a connectivity that would grow the knowledge and the capabilities of the additive manufacturing community.
3) Feasibility tests and capability demonstrations with a specific target should be developed in partnership with industry, to improve their understanding of the capabilities of the synchrotron-based technique, while looking at moving toward a large-scale experiment.

4.2. Table 2: Imaging / Spectroscopy

Moderator: Juergen Thieme, Brookhaven National Laboratory

1) Approaching additive manufacturing: the overall knowledge in 3D printing of metals and ceramics is not established enough to guarantee the quality of printed parts in comparison to standard subtractive manufacturing. On the path to validate methods for quality and failure analysis in additive manufacturing, the standard techniques already accepted in the established manufacturing industry should be the guide. Beamlines like HEX (at the moment under construction at NSLS II) would be very important for the manufacturing industry, because of the capability to characterize samples of relatively large dimensions and diverse shapes.
2) Critical factors: the most relevant present limitations faced by the 3D printing industry include the lack of routinely-adopted operando and in-situ experiments, along with the absence of a large quantity of data to build a consistent database of reference data for modeling validation. Overcoming such limitations would bring benefits to the understanding of various issues such as corrosion, segregation, porosity, and the impact of using recycled versus new material. However, the solution is not to be expected in just one analysis technique, but mostly in the multi-modal approach, using input information from different techniques at different levels of resolution.
3) Business model: industry needs a clear point of contact and a fast, easy access to the user's facilities. The present rapid access model is, at the moment, for experienced users, and this may be a limitation for industry, if no direct knowledge of use of material analysis facilities has been previously developed. Brookhaven Lab should provide the interface knowledge for the industry, where missing.
4) Testing: tests should be defined starting from standard materials and techniques, then moving to more important experiment such as in-situ stress/fatigue and corrosion.

Suggestions highlighted during the roundtable discussion are the following:

1) Brookhaven Lab should partner with standardization and metrology organizations (such as NIST and others) to develop a well-defined workflow for specific experiments.
2) Learning by doing – it would be useful to bring industrial partners to the beamline with an initial test experiment to allow them to gain knowledge of relevant techniques and familiarity with user access.
3) Similarly to what was suggested during the discussion of Table 1, feasibility tests with a specific target should be developed in partnership with the industry, as an initial step leading to possible future larger experiments.

4.3. Table 3: New Emerging Applications in 3DP

Moderator: Shomeek Mukhopadhyay, Obsidian Advanced Manufacturing

1. Precision applications: they may range among various sectors, from printable electronics, to certain aspects of nanotechnology like mask-less fabrication, microwave antenna designs for applications at higher frequencies specially 50GHz and above, metamaterials, engineering of new and innovative materials, and so on. The characteristics of the surface finishing of 3D printing using precision techniques is a fundamental aspect for most applications: for example, the high frequency applications of microwave antennas require high-smoothness surface finish in addition to having conductivities as close to bulk as possible.
2. Major barriers to widespread adoption: one hurdle to having a consistently smooth surface finish is the variability of the 3D printing process, both machine to machine, and run to run. It has been discussed that attention should be directed to possibly control some of the parameters of the 3D printing process by controlling the power variations using proportional-integral-derivative (PID) control or feedback loops. Additionally, the presence of more 'in-situ' metrology has been discussed specially for high-end and precision applications; it has been pointed out that this approach may actually limit the throughput for commercial production, thus becoming an issue. Another suggested way to mitigate variability in the additive manufacturing production process could be through robust design and software optimization.
3. Acceptance of new materials and processes: another important point that was raised is that most conventional or classical subtractive manufacturing will not/do not want to use untested materials and methods, but they rather prefer to develop new powders for powder based additive manufacturing processes. Some new materials that came up in the discussion included materials with gradient properties and/or layered bulk properties.

However, relevant aspects of the behavior of new application of 3D printed materials are not understood, such as what happens when we mix ceramic and metal powders and try to sinter them.

4. Possible further application areas: there may be room for relevant applications of 3D printing techniques in areas of designer materials and manufacturing. Furthermore, it has been pointed out that ceramic 3D printing is a widely open field, still relatively underdeveloped in comparison with the 3D printing of metals and polymers. For example, achieving the 3D printing of industrially relevant ceramics like silicon carbide may have a huge impact in the industry.

Suggestions highlighted during the roundtable discussion are the following:

1. We need to think outside the box: we need to envision a better process control and the possibility to move away from the predominant use of powders.
2. The testing and validation process of products is too long and expensive specially for small and medium sized businesses.
3. A dedicated portal for industrial businesses would be convenient to partner with Brookhaven Lab. There are a lot of problems which require quick turnaround for the industry. The current setup for partnering is inadequate.

4.4. Table 4: Partnering Agreements with Brookhaven Lab

Various technology transfer vehicles were discussed. The focus was on Agreements for Commercializing Technology (ACT), Strategic Partnership Projects, and Cooperative Research and Development Agreements (CRADA). The various parties were seeking guidance on how to partner with a DOE National Laboratory. The discussion was focused on the flexibility of the ACT mechanism and in-kind contributions on CRADAs.

Suggestions highlighted during the roundtable discussion are the following:

A flexible and approachable mechanism for industry to partner with BNL will be desirable. To become a user to access the user facilities, industry can sign non-proprietary or/and proprietary user agreements to start their research at BNL. A group of companies can submit one umbrella proposal to request beamtime. Details of user access can be further discussed with the industrial program office.

Appendix 1. Workshop Agenda

Appendix 2. Matrix of Technology Challenges vs Synchrotron and Electron Tools in BNL

ADDITIVE MANUFACTURING MATRIX		Technology Issues							
		Residual / Applied static stress	Applied cyclic stress (fatigue)	Creep/Strain (hot isostatic pressing)	Cracks/Porosity	Corrosion	Surface finish state/chemistry	Elemental segregation	Printed parts performance
Capabilities	XAS					Chemical state Local atomic structure	Oxidation state Chemical structure	Element specific	Chemical structure
	XPCS								Shear thinning/ recovery Shear-induced alignment of filer Polymerization during curing Road-to-road inter-diffusion
	XPS					Chemical ID	Surface modulation	bulk/surface electronic structure	
	XRD/High Energy Dispersive Diffraction	Phase diagram Stress profile	Phase diagram Stress profile	Strain mapping		Structure changes			Structure characterization
	PDF			Nanoparticle disorder structure					Nanoparticles, atomic disorder
	SAXS/WAXS			Modeling for design	Crack structures			Boundary orientation	Particle size, shape
	TXM/Micro-CT	3D morphology for strain analysis	Curvature analysis to reveal stress distribution	Structure and chemical phase	Microstructure in 3D	Chemical mapping	Chemical mapping	Element specification	Particle 3D structure
	TEM/STEM/EELS			High temperature atomic resolution structure	Surface structure	Structure and charge exchange	Structure and charge exchange	Element identification	High temperature nanoparticle structure evolution
	Raman spectroscopy					Bond forming and breaking	Adsorption mechanism	Element identification	Activity test
	Nanofabrication	CFN provide start of art nanofabrication methods for nanofabrication by design							
	Theory modeling	CFN theory group provides theory modeling to correlate structure characterization and performance analysis							

Appendix 3. List of Participants

LIST OF ATTENDEES

Name	Affiliation	Email
Abeykoon, Milinda	Brookhaven National Laboratory	aabeykoon@bnl.gov
Aguayo, J. Rafael	Stony Brook University	rafael@millennialtd.com
Amos, Peter	Obsidian Advanced Manufacturing LLC	peter@obsidianAM.net
Anerella, Michael	Brookhaven National Laboratory	mda@bnl.gov
Badesha, Santokh S.	Xerox Corp.	Santokh.badesha@xerox.com
Bechtold, Bob	HARBEC	BXB@harbec.com
Bechtold, Michael	OptiPro Systems	mike@optipro.dom
Brooks, Adam	EWI	Abrooks@ewi.org
Burkhardt, Bryanna M.	Brookhaven National Laboratory	burkhb@rpi.edu
Butcher, Thomas	Brookhaven National Laboratory	butcher@bnl.gov
Campanelli, Nick	Curtiss-Wright–Target Rock	ncampanelli@curtisswright.com
Chockalingam, Sreekumar	SRS Holdings LLC	sreekumarchockalingam@gmail.com
Clewis, Vaughan	Sono-Teck Corporation	vclewis@sono-tek.com
Coccorese, Ginny	Brookhaven National Laboratory	vcoccorese@bnl.gov
Colli, Alessandra	Brookhaven National Laboratory	acolli@bnl.gov
Dickey, Kevin	NTopology	kevindickey@ntopology.com
Drakopoulos, Michael	Brookhaven National Laboratory	drakopoulos@bnl.gov
Everhart, Wesley	Kansas City National Security Campus	weverhart@kcp.com
Fishman, Zachary	Yale University	Zachary.fishman@yale.edu
Funke, Chris	Obsidian Advanced Manufacturing	cfunke@obsidianam.net
Gudla, Pradeep	Async Computing LLC	pkgudla@async-computing.com
Gupta, Vipul	General Electric Research	Vipul.k.gupta@ge.com
Halada, Gary	Stony Brook University	Gary.halada@stonybrook.edu
Hanlon, Linda	Brookhaven National Laboratory	hanlon@bnl.gov
Hocker, John-Andrew	NASA Langley Research Center	John-andrew.s.hocker@nasa.gov
Hollenbeck, Michael	Optisys	Michael.hollenbeck@optisys.tech
Hunt, Erick	Brookhaven National Laboratory	ehunt@bnl.gov
Ivankovic, Andre	Launcher	andre@launcherspace.com
Kelly, Shawn	Oerlikon AM	Shawn.kelly@oerlikon.com
Kim, Bruce	City College of New York	Bkim91us@gmail.com
Laasch, Cara	Brookhaven National Laboratory	laasch@bnl.gov
Levine, Lyle	NIST	Lyle.levine@nist.gov
Lewis, Daniel	Rensselaer Polytechnic Institute	Lewisd2@rpi.edu
Li, Dongsheng	Advanced Manufacturing LLC	Dongsheng.li@amllcct.com
Li, Hongfei	Chem3 LLC	hli@chemcubed.com
Loghin, Adrian	Simmetrix Inc.	loghin@simmetrix.com
Longtin, Jon	Stony Brook University	Jon.longtin@stonybrook.edu
McSweeney, Elspeth	Brookhaven National Laboratory	emcsweeney@bnl.gov
Mercredi, Adrian	Instrumentation	Adrian.mercredi@trimech.com
Morfopoulos, Janet	Brookhaven National Laboratory	morfopoulos@bnl.gov
Mukhopadhyay, Shomeek	Obsidian Advanced Manufacturing	shomeek@obsidianam.net

Name	Affiliation	Email
Murphy, Diana	Brookhaven National Laboratory	dfmurphy@bnl.gov
Ochoa Putman, Carol	Kitty Hawk Technology	Carol.o.putman@kittyhawktech.com
Oliver, Manny	U.S. Department of Energy	Manny.oliver@science.doe.gov
Petrash, Stanislas	Henkel Corporation	s.petrash@gmail.com
Pillai, Rajalekshmi	SRS Holdings LLC	Pillai.rajalekshmi200@gmail.com
Plunkett, Ken	Norsk Titanium	Ken.plunkett@norsktitanium.com
Risenhuber, Leslie	MITRE	lriese@mitre.org
Rock, Stephen	Rensselaer Polytechnic Institute	rocks@rpi.edu
Rooney, Christopher	NYSTAR	Christopher.rooney@esd.ny.gov
Sanchez-Grueso, Alejandro	CELLS-ALBA Synchrotron	asanchez@cells.ed
Schmidt, Wayde	United Technologies Research Center	schmidwr@utrc.utc.com
Schotte, Greg	Instrumentation	Schotte.greg@gmail.com
Skandan, Ganesh	NEI Corporation	gskandan@neicorporation.com
Solovyov, Vyacheslav	Stony Brook University	Vyacheslav.solovyov@stonybrook.edu
Stoia, Michael	The Boeing Company	Mike.stoia@boeing.com
Suhosky, Robert D.	Kitty Hawk Technologies	Dave.suhosky@kittyhawktech.com
Tatar, Samantha	Kansas City National Security Campus	statar@kcnsc.doe.gov
Torres Arango, Maria	Brookhaven National Laboratory	mtorresa@bnl.gov
Tseytlin, Simon	Tseytlin Consulting, Inc.	Simon.tseytlin-consulting.com
Tufarielllo, Justin	The MITRE Corporation	jtufariello@mitre.org
Tuffile, Charles	Bosch	Charles.tuffile@us.bosch.com
Velkoff, William	Curtiss-Wright	wvelkoff@curtisswright.com
Wang, Jun	Brookhaven National Laboratory	junwang@bnl.gov
Wang, Ping-Chuan	SUNY New Paltz	wangp@newpaltz.edu
Whelan, Timothy	Kansas City National Security Campus	twhelan@kcnsc.doe.gov
Xiao, Zhigang	Microcvd Corporation	George.xiao@microcvd.com
Yoo, Shinjae	Brookhaven National Laboratory	sjyoo@bnl.gov
Zangiacomi, Nicholas	Curtiss Wright	nzangiacomi@curtisswright.com
Zhang, Wu	Brookhaven National Laboratory	arling@bnl.gov
Zhong, Zhong	Brookhaven National Laboratory	zhong@bnl.gov