MEETING SUMMARY

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

Inspection/Monitoring to Meet Regulatory Requirements: Additive Manufacturing (AM) Standardization

December 8, 2021

*This virtual event brought together subject matter experts from various sectors for a discussion to further develop and refine the AMSC **Standardization Roadmap for Additive Manufacturing**, last published in June 2018. This included discussion of the following:*

- *What applied research, standards, guidance documents, or conformance programs exist/are in development for inspection/monitoring, especially in-situ process monitoring or nondestructive evaluation (NDE), to meet regulatory requirements of additively manufactured parts?*
- *What issues or gaps exist, particularly related to inspection/monitoring (in-situ or NDE), to facilitate certification of additively manufactured parts?*

Meeting Materials

Throughout this meeting report, speaker remarks are abbreviated and summarized to highlight key points. The meeting was recorded for those who wish to hear comments in full.

- Access the meeting recording.
- Access the master slide deck and complete set of meeting presentations. Individual presentation links also appear in this report alongside the name of the speaker.
- Access the meeting agenda and speaker bios.

Discussion Topic and Speaker
Welcome - Jim McCabe, Senior Director, Standards Facilitation, ANSI - Brandon Ribic, Ph.D., Technology Director, America Makes Jim McCabe and Brandon Ribic welcomed participants. Today's event is the latest in a series of events hosted by the AMSC. The morning session will be a series of presentations with Q&A. The afternoon will be a moderated panel discussion.
Session 1: Presentations on Applied Research, Industry Standards, Guidance Documents, Conformance Programs **Moderator: Jim McCabe, Senior Director, Standards Facilitation, ANSI** Jim McCabe introduced the morning speakers and invited them to make their presentations and answer questions submitted by audience members. Key points from the presentations are summarized. **Erin Lanigan, Materials Engineer | EM21, Damage Tolerance Branch, Non-Destructive Evaluation Team, NASA Marshall Space Flight Center (MSFC)** Presentation Link Erin Lanigan spoke about the role of NDE and in-situ monitoring in managing risk for AM space hardware at NASA. She described how NDE and in-situ monitoring is used in NASA's certification framework and how NASA qualifies NDE and in-situ monitoring systems to verify their reliability.

AM part certification for NASA is outlined in several documents. The first is **NASA-STD-6016C**, which is the general materials and processes requirements for all spacecraft hardware and also covers AM. There was previously a standard developed by MSFC for AM of laser powder bed fusion (LPBF). That's been adapted into **NASA-STD-6030**, which was released in the last year and covers all types of additive manufacturing. There's also an accompanying **NASA-STD-6033**, that covers equipment and facility control. NASA is working on a handbook that will come out pretty soon that will include some more specifics and case studies about how to apply these requirements.

NASA's classifications are based on several aspects of the risk of the AM part. The first is the consequence of failure. If it would be a high consequence of catastrophic failure, it's a class A part; if it's a low consequence of failure, then it's class B. If the risk to other aspects of the mission is not negligible, it remains class B; if it is negligible, then it can go into a special class C, that doesn't require any NDE or much verification (e.g., nonstructural parts). Within the primary classifications, there are sub-classifications based on structural demand (is it heavily loaded?) and AM risk (how difficult it is to build, the use of overhangs, complexity of the geometry, and inspectability of the part).

The NASA standard requires all class A parts to receive quantitative NDE with full coverage of the surface and volume of the part, including verifiable detection of the critical initial flaw size in critical damage tolerant parts. The inspection and coverage limitations need to be documented in the part production plan (PPP). The other requirement for class A parts is that they meet the Special NDE requirements in NASA-STD-5009, which is the standard for NDE of spaceflight hardware. Again, that needs to be documented in the PPP. For class B parts, which are the lower consequence of failure, those would have just NDE for process control, again with full coverage of the surface and volume. The main difference in this requirement is that the NDE approach does not need to demonstrate verifiable detection of a critical initial flaw size. The basic requirements of NASA-STD-5009 still need to be followed, such as the use of physical reference standards and documentation of the procedure, but not the Special NDE requirements.

There is some language in the standard that allows the use of passive in-situ monitoring as a quantitative indicator of part quality, if qualified in a manner analogous to NDE. However, this may not replace NDE. There is a paradigm shift in using in-situ monitoring like NDE. In the case of melt pool monitoring and many other techniques, you're monitoring the process and inferring what happens in the part. Using this as a quantitative indicator of part quality would require a thorough understanding of the physical basis for what you're measuring, what is actually happening in the part, and a proven causal correlation of those measured phenomena to a defined defective process state in the final part. It would also require a statistical analysis of the probability of detection. If qualified in this way, in-situ monitoring can be used to complement NDE and help certify a part. It's encouraged to have in-situ monitoring on any AM machines that are being used for certified parts as a source of process control data, and to help guide targeted inspection.

There are several different aspects of certification where in-situ monitoring can be used: as process control data, when you're developing a qualified material process (QMP); in part classification, to reduce AM risk; in the part production plan, as a qualified defect screening action; and in long-term statistical process control. Currently, the certification approach does not allow the use of adaptive or closed-loop feedback control systems that change the process in response to monitoring data, because the QMP must be a locked process.

In sum, there's a place for both NDE and in-situ monitoring in the NASA certification approach. If you want to use in-situ monitoring for quantitative part quality, it would need to be qualified. The main challenge is not only detecting the indication, but also correlating that to a defect in the finished part. Qualifying a closed-loop adaptive system is something for which NASA will have to develop a new approach.

Q&A

You mentioned several NASA standards. What's your perspective on the development of public standards? I take that to mean voluntary consensus standards developed by independent standards developing

organizations. Related to that, how does NASA consider using those public standards, when there's already a NASA standard that exists.
As many public standards as can be developed, the better. We're involved in developing some of those. There's an ASTM guide for NDE of additive that we helped work on as well as an ASTM guide for in-situ monitoring. Those don't really have requirements, but are more guidance. Those are always helpful. There was a really big push to get the Marshall standard out a few years back and to get the new NASA standard out now because there wasn't a lot of available guidance to go from. We're hoping that would serve as a good framework for others as well. The integration of other standards is not something we've really had to deal with yet because there aren't a lot of requirements that directly overlap. But as any new ASTM or ISO standards come out that are applicable, we would try to integrate those into the NASA approach so that they're consistent.

What's the best way to get involved with NASA to certify a method of in-situ monitoring? You mentioned that there are a couple different certifications: accuracy of process monitoring and accuracy of the final part quality with the features monitored.
We're definitely working in-house, and through some collaborations, trying to develop that framework and get some data on those correlations. If we had a vendor who was trying to qualify a process, how we would want them to prove that? It's definitely something we are very actively working on. You can reach out to me, and I can get you some more information. We have a few projects working with small businesses in developing monitoring techniques, and some partnerships with universities getting more into the correlation of indications in CT and in-situ data.

The perception is that NASA views in-situ monitoring and ex-situ NDE in a similar way. How can we qualify in-situ monitoring when qualified NDE methods do not exist, for example, uninspectable parts?
Qualifying a CT method, what we have in mind for that, would be verifying that you can find the right defect, type, and size in a part. It is, of course, always a challenge to try to simulate artificial defects in a part that would be representative of if you had a real defect. But developing artifacts and proving that would be the general approach for NDE. It would be similar for in-situ monitoring. It is a challenge in both cases to try to qualify those processes, to have reliable detection. In-situ monitoring is not really thought of the same as NDE. It's definitely a big leap from the in-process indications versus knowing that there's an actual defect in the part. To be able to use it like NDE in that qualified manner would require a correlation between monitoring data in NDE that we haven't had implemented yet. We haven't seen that yet. But that would be the ideal.

What are the techniques that qualify for verifying the defects for NASA standards?
There aren't necessarily certain NDE techniques called out. It would just need to be able to meet the requirements of **NASA-STD-5009** for NDE**.** The methods listed in 5009 are a lot of the standard methods like penetrant, eddy current, magnetic particle (although we haven't really used that on additive), ultrasonic, and x-ray. Computed tomography (CT) is actually not listed as one of the standard methods but anything that isn't a standard method in 5009 falls under that Special NDE category. Since AM falls under the Special NDE category anyway, it's really open to any inspection method that can meet the requirements and basically show a probability of detection of 90% detection at 95% confidence.

Do you think benchmarking of in-process monitoring/feedback systems would be useful and how would you approach it?
Yeah, that would be good. We haven't really worked in that area much. But any system where we can have a baseline of knowing how it works in reliable detection, for a different material or different additive method, would be a great starting point for being able to apply it, and making sure that we can get the reliable detection that we need.

One of the biggest limitations with sensors today seems to be the issue of false positives of defects in laser powder bed fusion. Is NASA defining algorithm quality constraints, for example, setting statistical limits on false positives, or is NASA waiting for industry to tackle challenges like these?
That is something that we're working towards and will definitely be a big thing we'll have to look into if we are qualifying an in-situ monitoring system. We haven't done so yet but we are looking into some developments

with private companies, and with university partners, developing algorithms for processing in-situ data, and false positives are a huge problem. A big aspect that we've found to be pretty reliable is if an indication persists through multiple layers. That would probably be one aspect and then, obviously, things like the shape and the intensity are used by a lot of image processing algorithms. It's really a matter of correlating the indications with the CT data. But if there are a lot of false positives in the indications, then that would not be considered a very good correlation, if that makes sense. It wouldn't just be, yes, we found every defect in CT and the in-situ monitoring data. It would be we only found those or maybe a few false positives that we had to investigate. But off the mark false positives wouldn't be good. And there is a threshold for that in NASA-STD-5009 in the probability of detection approach.

Is NASA mostly focused on metal AM and NDE and or have you also investigated NDE for polymer AM?
We are mostly focused on metal. The reasoning for that is that polymer parts would generally be only used for class C, non-structural parts. We wouldn't need to do NDE on those. We are looking into NDE and methods for certification of parts manufactured in space. One of the methods that we're developing for the space station is bound metal deposition, which prints polymers with metal particles, and then debinds and sinters that together. So, we do have some in-situ monitoring systems that are geared towards polymers and we have some early stage efforts, considering NDE technologies for the space station, Gateway, and beyond. We are considering that we might have polymer parts at some point in that process.

Dr. Ehsan Toyserkani, Professor and Canada Research Chair in Additive Manufacturing, University of Waterloo
Presentation Link
Dr. Ehsan Toyserkani presented research being conducted at the Multi-Scale Additive Manufacturing (MSAM) Laboratory at the University of Waterloo, on a systemic approach to in-situ photodiode-based monitoring and analytical machine learning defect detection algorithms. His remarks included a brief overview of the MSAM and defect healing using an intermittent controller.

The University of Waterloo has been recognized as the most innovative university in Canada for the last 32 years. It's ranked first in Canada and 22nd in the world in the 2021 Pitchbook top 50 colleges for founders. The MSAM is the most comprehensive additive manufacturing academic center in Canada. It has world class AM equipment and comprehensive research programs.

MSAM is conducting a wide range of R&D for different engineering and medical sectors. It works on material and process development and AM adoption for applications in aerospace, communication, automotive, and medical, and in-situ monitoring and quality assurance for both LPBF and laser directed energy deposition (LDED). It has systems for medical monitoring and optical tomography.

Like all conventional techniques, in-situ monitoring and quality assurance procedures/tools for AM are of the utmost importance in aiding manufacturers in quality management and certification to confidently step into low- and high-volume manufacturing. In-situ monitoring and its impact on the process health monitoring call for the development of standards. ASTM, ISO, and other standards organizations are working very hard to develop concrete, reliable standards as best practices or specifications for industry.

There are challenges with in-situ monitoring and quality assurance for LPBF specifically. Most in-situ monitoring technologies for LBPF are not yet advanced enough to detect process disturbances reliably with high level of confidence. Many developments have been carried on in-house developed systems, making it hard to replicate. There are too many intrinsic and extrinsic parameters involved in LPBF, causing major nonlinear, non-harmonic disturbances during the process. The requirement to have an adaptive calibration platform due to temperature dependency of intrinsic parameters should be addressed. There is not adequate resolution, accuracy and sampling frequency in monitoring devices to count for small size defects (<50 micron). There is a lack of model-based monitoring and quality assurance platforms.

To address some of these challenges, MSAM proposed a research program with EOS a few years ago with the objective to systematically look at photodiode-based monitoring devices and how they can help manufacturers when it comes to quality assurance. Dr. Toyserkanki described the program in detail.

The study concluded that the threshold levels and sampling windows obtained through the systemic approach, applied to printed parts with intentional pores, facilitate a model-based detection platform to identify randomized porosities. The successful detection is limited to pores larger than 120 microns. The level of confidence in the detection is more than 75%. With new technical development and improving the hardware resolution and frequency, the detection of finer pores is on the horizon. A work item (**ASTM WK76983**) has recently been registered to craft a best practice under “In-situ Defect Detection and Analysis.” They are hoping to collect feedback from peers on the developed approach.

Q&A

Do you think your systematic approach could at some point serve as a standard method of quantifying monitoring, for point of delivery or comparing sensor monitoring capabilities?
Yeah, this is our hope. We would like to really just see whether we would be able to use it as a benchmark or as a platform to quantify what we can get out of medical monitoring and other monitoring devices like optical tomography. One of our current activities is to really merge the data we are getting from medical monitoring and optical tomography. We see some potential, but to be honest with you, it's very tough. It’s very tough to concretely say with a high level of assurance that what we are developing would be reliable methodologies that would be accepted by industry. From an academic perspective, it’s fantastic. But, when it comes to real practice, I cannot really say at the moment.

Is there a public standard for voxelization data storage that the additive industry uses?
I'm not one hundred percent sure. We are digging into available standards. This is our first practice with ASTM. I haven't seen anything associated with voxelization when it comes to monitoring and quality assurance. We haven’t done our homework yet entirely. The team is doing very massive research to ensure we refer to the right standards when we develop the draft of our own standard under that work item that I showed you.

Recognizing the range of machine learning algorithms and approaches under development today, is there a need for standard test cases/functions in order to baseline algorithm reliability/performance?
Yes, absolutely, we need it. We see some different approaches when it comes to machine learning specifically for supervised methods. People actually provide some labeling, scoring that are so subjective. We need to really come up with standards when it comes to machine learning and even analytical methods.

Does the feedback add any delays or is it another pass that you do?
No, nothing at this stage. That algorithm is in fact computed very quickly. We are talking about something in the range of less than 500 milliseconds. During the time that the culture is putting the new layers, so the process is done, the new power map has been identified. And the laser power would be selectively changed during the print on that newer slice. It is not a real time control. Some people call it feed forward. I usually don't go with feed forward because feed forward within the field of controlled classic is really real time. It's not real time so that's why we go with a controller that can fix the parameters for the following layer.

Dr. Abdalla Nassar, Associate Research Professor, Head of Process Physics, Analytics, and Engineering Department, Applied Research Laboratory, Pennsylvania State University Presentation Link
Dr. Abdalla Nassar presented on in-situ monitoring of process defects and avenues for control/correction in laser-based metal additive manufacturing. The Applied Research Laboratory (ARL) at Penn State is a university affiliated research center within Penn State that also functions essentially as a government contractor within the university. That allows ARL to work on very fundamental science problems as well as developing things that relate to actual implementation in the field.

It’s hard to differentiate the hype and the reality on in-situ sensing for AM. The number of publications on in-situ monitoring has exploded over the past decade. That raises the question how much progress have we made.

There are photodiodes systems, camera systems on almost every commercial machine available for purchase today. But no one could claim that those in-situ monitoring systems are a substitute for NDE methods or that they have proved particularly useful in complementing NDE methods. This presentation addresses key issues and where standards development might be able to help.

Traditional process performance qualification methods require a repetitive manufacturing process to achieve products that exhibit equivalent performance. However, AM has the ability to do very complicated things: one-off products, small lot production, etc. This complexity makes qualifying a process very difficult. The current standards that are available can work for a particular type of product. These same inspection techniques may not work for something that has lattice type structures and that is a large bulk item.

In-situ monitoring is useful when particular process steps are highly variable, depending on the geometry and the material system. It can augment process and part qualification and enable process control. Today, most machine manufacturers and many end users have perfected the art of process mapping. Even so, process monitoring can help with machine health monitoring, monitoring the laser power output and scanner errors. There are some standards covering machine configuration and settings. But even with optimized processing conditions, there is a need to better understand the different flaws that may occur.

There are different approaches to process monitoring, for example, using photodiodes-based data, pyrometers, spectrometers, acoustic sensors, layer-wise imaging. There are high-fidelity sensing approaches that are not meant to be applied to commercial systems, for example, high speed visible imaging, x-ray-based imaging, high resolution tomography, etc. There are also complementary post-process inspection methods. Various types of sensors can be deployed. There are co-axial configuration sensors and staring configuration sensors. There are single point detectors, which are very scalable (e.g. photodiodes microphones), and there are array type detectors (e.g., cameras) that are not so scalable but provide significant amounts of data. Monitoring approaches differ for powder bed fusion and directed energy deposition.

Fundamental challenges include: the wide range of time and length scales; system interfacing and data acquisition; a replication crisis (too many variables); the volume of data being generated is enormous particularly for PBF; and alignment/registration uncertainty. Standards can help to meet these challenges. When it comes to data collection, alignment and registration, a machine learning approach can help. Fundamentally, data needs to be correlated to where a defect occurred.

Q&A

You mentioned some ASTM work items. The question is whether certain aspects are documented considerations in those, specifically sensor framework design, field of view, sampling frequency?
Yeah, that work item is very long. It does include some discussion of each of those items and it references some existing standards. Things like field of view, resolution, etc. There are well developed standards for those types of things when it comes to camera-based systems. We don’t try to reinvent the wheel. A lot of the heavy lifting was done by Brandon Lane at NIST. Erin and I and lots of people are on that group. A lot of what was intended in that standard is to introduce those items in the context of additive manufacturing, particularly powder bed fusion as well as to reference the reader to the existing standards that are out there.

Any deep network machine learning or is it primarily conventional neural net AI for classifying part acceptability?
The architectures that we've worked with have been primarily using shallow neural net. We've used both shallow neural net and convolutional neural net (CNN). We don't like to use lots and lots of hidden layers. When you use a neural network, you're already working with a black box, so you don't really know what it's doing. When you use a CNN, it even gets worse. The more layers you add, the more you're kind of in the dark. We found that using a reasonably shallow neural net or a CNN has given us pretty good performance. As we grow more sophisticated, we try to add more layers and maybe use a combination. When you work with machine learning experts, it's really more of a black art than science at this point, so we try lots of different architectures and see what works best. The hard part is not the machine learning; it’s getting your data in the correct format,

being able to figure out the registration, how to compare a neighborhood from your in-situ sensor data to a neighborhood of your CT data, and what metrics to pull in. How to do the dimensionality reduction piece before you throw something into a neural net—that's the hard part.

Is it sufficient to fix the part geometry in order to develop these sensor frameworks, or do we need fully defined geometries and processes to provide a suitable starting point for assessing sensor capability?
I don't know if I'm the right person to answer that quite honestly. I would point that to Erin or an organization that really needs to implement these parts. In my opinion, I think that if you have a well- defined geometry on one machine with one material system, it makes sense that you can record sensor data from that build and compare it to each subsequent build to look for systematic variations. I think that's an easy case to make where you can look at systematic variations in sensor signatures from repeated builds. Unfortunately, with AM, typically, we're not doing that. We want to build lots of complicated things in very small lots. So, yeah, I think there's a case to be made for that. I don't know how useful that is compared to being able to develop methods that can detect flaws from a variety of geometries.

Solomon Duning, Research Engineer, Additive Manufacturing Technology Development, Structural Materials, University of Dayton Research Institute (UDRI) Presentation Link
Solomon Duning's presentation provided an overview of an America Makes project on reducing "time to first good AM part" through in-situ sensor driven NDE. The project highlights a lot of what the other panelists talked about in terms of the different challenges and things in the in-situ monitoring space that industry has to overcome. The project includes several partners each with a different role.

Metal AM offers a lot of design freedom, but that comes at a cost. It is an iterative trial and error printing process to lock down parameters for specific parts, especially when complex geometries are involved. Trying to get to that first good part can mean a lot of time-consuming, post-inspection steps, long lead times, and high cost. Often when high criticality parts are involved, high resolution NDE is needed to identify nonconformances. Depending on the geometry and material, it may not be feasible to achieve that for the entire part, from limitations of the machine or the amount of available data. This project aims to use in-situ sensing to inform data-driven point of concern inspections. It would be great to use in-situ sensing to replace things like NDE but there's a huge problem of correlating all of the in-situ data anomalies to actual part nonconformances.

The first phase of the project showed a real example of how Northrop Grumman fabricated six heat exchangers following all the processing steps only to discover nonconformances during the NDE phase. The parts failed, costing the company time and money. The issue becomes catching the nonconformances earlier using in-situ sensing techniques to tailor the NDE inspections.

The next phase involved part printing at UDRI using an open architecture LPBF system. The in-situ sensing system used was AMSENSE, a product offered by Open Additive. The system opens up the raw data so users can write their own plug-ins to analyze the data in-situ. This is intended to avoid the black box nature of a lot of commercial sensing platforms that other speakers mentioned. Putting the same third-party sensor suite on multiple different machine modalities can facilitate understanding of machine variability and anomalies.

Subsequent phases of the project included correlating the in-situ data to the CT using thermal tomography and a CNN machine learning network. The project showed some correlation between the high-density spatter region and the region of porosity in CT. It also showed a lower density spatter in-situ associated with lower porosity CT. As other speakers have mentioned, in-situ can be used to help augment CT but it is not on its own a suitable replacement for CT and other NDE methods.

Next steps include correlation database maturation, meaning getting better with all of the different techniques for correlating in-situ anomalies to end part defects. This can be done through registration improvements, trying different geometries, materials, and machines. It's important to label the data that's coming off the sensors and the different print jobs, and keeping track of the parameters so that predictions are not made based on inadequate information. Other steps include analysis of other anomaly types than what was focused on in this project (spatter), and feature level analysis of data.

Q&A

There's a question on how labor intensive the analysis is for defect detection. Are there techniques or recommended practices which can help to address the cost and time related to inspection procedure development or cycle time?

Yeah, it is a very labor-intensive process, not only to inspect these parts, but to generate all the registration from our NDE data or CT data to our in-situ data. I think a lot of that has to be more standardized than it is. I talked earlier about the tribal knowledge of AM where to build a part it's a lot of tribal knowledge when designers go in to figure out how to orient the part and everything. The sensor community stepped in to better inform how we're building these parts. However, a big challenge is a lot of different people that are doing sensors are making their own black box within the sensors themselves. So not being very open about what's going on and how things are being registered and correlated. It's become tribal knowledge with sensors. Some standardization of these processes would go a long way. Developing frameworks to register data in a very methodical way, so we can get to that kind of correlation standpoint. So we understand what data we're looking at, how it's oriented relative to everything, and flesh that out. So we can have more confidence in our correlations.

Is there anything that you can elaborate on vis a vis registration improvement?

Simple Voxel joined the program late and, unfortunately, their material wasn't cleared for these slides. But they did a great approach of a voxel-based registration, bringing in both data sets and this voxel representation and then they were able to align and register that data to a pretty accurate degree. That's one phase of it, that registration of getting the two data sets. But there's also the calibration of the sensors themselves, of how they're calibrating, in this instance, an off-axis sensor to machine coordinates. What's going into that tomography and scaling correction step before you even get to the registration. So, that's kind of going into being open about how we're analyzing this data. If we're open with how things are calibrated to get from the camera space to the build coordinate space, then we can better understand the errors associated with our registration.

Robert Badrak, Materials Consultant, Weatherford (on behalf of AMPP: Association for Materials Protection and Performance) Presentation Link

Bob Badrak spoke about a relatively new AMPP project, TR21522 Corrosion Testing for Additive Manufacturing. By way of background, a gap was identified that global specifications did not really address corrosion issues related to AM. So, a work group was formed to prepare a technical report that describes the AM attributes that have strong effects on performance as related to corrosion associated failure degradation mechanisms and ways to measure this performance that were specific to AM.

The goals of the project are to: identify corrosion failure mechanisms that are affected by AM, AM attributes that affect the corrosion mechanism, and tests that measure performance by corrosion mechanism; provide guidance on test details/examinations to better assess performance; and identify gaps in where current test/examination details are not suitable for AM.

The current scope envisions that the technical report will include the current state of knowledge and gap analysis on corrosion testing of metallic materials relevant for oil and gas applications for AM via primarily LPBF and wire arc additive manufacturing (WAAM). The scope recognizes that many variables may not be sufficiently detailed at this time for the assessment of performance of AM products; some variables such as microstructure, post build processing, surface condition, residual stress, physical defects and selection of representative test specimens (size and/or geometry) for a finished product are addressed. The report will contain recommendations for an approach for corrosion and environmental cracking assessment of AM material, including test details that are relevant to the AM processes for some specific cases. The technical report will provide the foundation for the preparation of test standard(s) that apply to AM products.

Mr. Badrak reviewed the subteams responsible for various aspects of the project and the preliminary report outline. He noted that this effort is really not centric to NDE and in-situ monitoring like the rest of the panelists today. However, they have to review the details of inspection to determine whether a component meets the performance requirement for a particular application. The group has undertaken an extensive literature review and categorized it by mechanism, material, and relevance. The group includes AM OEMs and end part users and is largely comprised of representatives from the energy industry, especially oil and gas.

Some initial inspection details include: selection and condition of test specimens used to assess resistance to the associated corrosion mechanisms; relevance of test specimen to component; surface inspection including residual stress (non-destructive); process & component inspection/test relationship; and NDE versus destructive tests.

The project timeline envisions completion of the literature review in March 2022, with literature analysis in May. Teams will be assigned in June to begin drafting. An initial draft report is targeted for October with the final draft by December. Following review and comments by experts around the world, the report is targeted to be published in early 2023.

Q&A

How do you feel your efforts are creating a knowledge base which lends to effective monitoring and inspection methods? What key indicators or metrics do you feel warrant further quantitative verification (i.e., measurement)?

I can address the second one better than the first one. We're familiar with the CT scans and with all of the surface measurement techniques that are out there. We’re very interested in all the in-situ monitoring. The gentlemen at Penn State indicated they're trying to correlate the in-situ details and relating that to microstructure. Since microstructure is very important for corrosion mechanisms, we are very interested. For corrosion mechanisms, the environment – material interface is critical. It's not just a surface, because when hydrogen is an issue, it migrates into the pores and defects and anomalies in the microstructures. All these things are very important. In terms of inspection, the barriers to us are the relationships between in-situ monitoring and the microstructure. The other barrier is not all areas of concern are the surface areas. What do you do with all these internal pores and cavities that you intentionally have in there, for flow, for example? How do you inspect those and have some reliability? I call that a big gap. That's an area where we're going to have to do some work. I mentioned residual stress. It very strongly comes into play for a couple of the corrosion mechanisms: corrosion fatigue, obviously, and regular fatigue, and also for stress corrosion cracking. We all worry about applied stress. We can look at the product design. We can make some estimates of where what stress occurs, in what direction, things like that. But residual stress also has a very large role. There are some papers that we've identified. In fact, Weatherford has been active in a couple of them, looking at residual stress as a function of distance from the surface before and after post-processing and noticing some very interesting characteristics that relate to that. That will probably become part of what comes out of this. When it comes to residual stress, is it compressive, beneficial for fatigue and for stress corrosion cracking? If it's tensile, it's just the opposite. So, I see that as an area that's going to have some work. To recap: the things that are causing us grief are the relationship of the monitoring processes that exists today with microstructure. Examining microstructure is typically a destructive process. We don't want to destroy things if we don't have to. We might look at specimens that will go along with the build. What's the degree of assurance you have that the sample that you evaluate corresponds to the AM component where it may be critical? I think that answers the second part. Can you repeat the first part again?

Sure. How do you feel your efforts are creating a knowledge base to help with effective monitoring inspection methods overall?

I think it's going to aid it because there's nothing out there today in a specification that really links additive manufacturing details, in terms of inspection or in manufacturing, with the corrosion mechanisms. We're interested in corrosion and the specifications haven't really addressed that. The first one that even touches that is the **API specification 20S**, but there's not much detail even in that because it's early on. It's a gap. I see this technical report as providing a springboard for the future in terms of the knowledge base in this area. How do we use our existing specifications that are related to testing and measurement for assurance in additive manufacturing, identifying and providing some guidance – maybe using those specifications in a different way – or creating a new specification. I see it as valuable for this series of mechanisms that are related to corrosion.

Session 2: Panel Discussion on Inspection/Monitoring (in-situ or NDE) to Facilitate Certification of AM parts

Moderator: Brandon Ribic, Ph.D., Technology Director, America Makes

Brandon Ribic observed that today's conversation is fundamentally about confirming that products made using additive manufacturing are sufficient for the application for which they are intended. He noted that AMSC is about driving coordination and collaboration among standards developing organizations and the subject matter experts from the research domain and the standards domain. These periodic AMSC events are about sharing information to help us all get our arms around the standards landscape. He invited each of the speakers to introduce themselves and make brief opening remarks. He then moderated the discussion.

Opening Remarks

Eric Biedermann, Engineering Manager, Vibrant Corporation

Vibrant Corporation is a nondestructive evaluation services company. We provide process compensated resonance testing (PCRT) services to aerospace, power generation, automotive, and many other industries. We're very active in the additive manufacturing realm. It's one of the biggest growth areas for us. In addition to our work on actual inspection, we're very active in the development of standards pertaining to nondestructive evaluation and additive manufacturing. Personally, I am active in the ASTM E07 committee for nondestructive testing as well as the ASTM F42 committee for additive manufacturing. I've been involved in several standard practices specific to PCRT, our inspection approach. There are also standards like **ASTM E3166** that was the effort led by Jess Waller to develop a standard guide for NDE methods for metal aerospace parts made with AM. In F42, we've been working with Steve James on the development of a new standard practice, **ASTM WK75329**, for nondestructive testing inspection levels and acceptance criteria for parts made with laser beam powder bed fusion. So, there's a lot of active standards work going on right now. This landscape is still being defined and we're working hard to fill in gaps between legacy standards that may have been made for other manufacturing processes and to understand what from that body of work can be adapted and then what new work needs to be created to fill those gaps. I've also been involved in the ISO realm. Ben Dutton has led a couple of efforts on the **ISO/ASTM DTR 52905** and **ISO/ASTM PRF TR 52906** to develop guides for NDE for AM as well as seeded flawed definition. I contributed a little bit to those as well.

Nicholas Mulé, Director, Additive Manufacturing Intelligence Center, Boeing Additive Manufacturing

I lead a team within Boeing that is looking to develop additive manufacturing across the company. All the different business units are wanting to take additive and employ it on their different products or platforms, looking at what needs to be done from a technology maturation standpoint to do that safely and reliably. My team has a focus on modeling and simulation and developing the additive digital thread. It's a very wide scope. Within that there's a lot of work on how do we harness and leverage additive manufacturing data, from engineering through manufacturing and post-processing. My team is working a lot with NDE teams and the Boeing development teams on how do we leverage in-situ data, how do we tie it back to all the other datasets to make interpretable decisions. Behind that is a slew of research. We are aiming to achieve a fundamental understanding of what this data is, how do we validate it, and how does it get integrated with a bigger picture of adopting additive. I've been involved with metal additive for over 10 years in aerospace so I've done a lot of research with in-situ within different aspects of material and processing maturation. In this new role I'm able to tie that all together to help streamline and accelerate adoption of additive.

Dr. Cambre Kelly, Vice President of Research and Technology, restor3D

I lead the research and upstream technology development team at restore3D. We are a medical device business focused on personalized orthopedic devices, both implants and instruments that we're producing through various AM methods. We are kind of unique for a business of our size. We're an early stage startup, but we own all of our design and manufacturing in-house. For us, process controls, monitoring, inspection, are all absolutely critical to our process. We’re heavily regulated by the FDA. As we look to scale our business, we are working to improve our monitoring and inspection methods to be able to produce more parts at our facility. I'm also affiliated with Duke University and do a lot of research through different lab groups there. I’m also a member of the ASTM F42 committee. I'm currently working with the ASTM AM CoE team that is trying to develop a destructive test method for lattice testing of additively manufacturing lattices. Part of that in the next stage would be to look for NDE methods around lattices too.

Patrick Howard, Consulting Engineer Nondestructive Investigation, GE Aviation

I work in Cincinnati in the division of GE that makes, among other things, the aircraft engines that go on most of the commercial airplanes that fly today. I also do some work on the military side. We are working on a lot of advanced manufacturing techniques including ceramic composites and additive for metals. As a consulting engineer, I work with the people developing the new manufacturing methods trying to identify the proper nondestructive testing methods to work with those new components. I work with the design engineers to make sure all the requirements are aligned with the inspection techniques as we move those forward through the MRL maturation process here at GE Aviation. I am also involved with the ASTM E07 and F42 committees and the development of a lot of the standards that Eric Biederman mentioned. In addition to the one’s Eric mentioned, I will mention there’s a standard for the CT inspection of additive that's being developed by E07. Thomas Maeder from Boeing is leading that effort.

Dr. Abdalla Nassar, Head of Process Physics, Analytics, and Engineering Department, Associate Research Professor, Applied Research Laboratory, Pennsylvania State University

I work in applied research at Penn State. We do lots of different things; among those are in-situ process monitoring and control. We've had several projects for a bit over a decade on process monitoring and control of both powder bed fusion and directed energy deposition systems. In addition, we do some materials development work, some processes work, and some more fundamental research as well. We play across TRL levels because we're a university affiliated research lab, and we're intimately connected with Penn State University. We do research across very low TRL levels. For the very TRL high levels, we collaborate with both government and industry partners to actually bring solutions to the field. We’re involved with several standards activities through ASTM F42. We have an America Makes program involving ASTM that looks at means to do defect mitigation methods and we’re hoping that that becomes a work item soon.

Gene Kulesha, Senior Director, Advanced Engineering, Onkos Surgical

Onkos Surgical is a small startup out of New Jersey that is focused pretty exclusively on making implants and instruments for people suffering from a variety of oncological orthopedic afflictions, an area that really hasn't been a focus of a lot of other companies. We also create implants and instruments for what we call revision surgeries. These are orthopedic procedures that occur a number of years after someone gets their index or their primary surgical intervention. I used to work for one of the big orthopedic companies, Stryker. I was involved in researching, developing, and leading some of the activities there in 3D printing, specifically powder bed fusion of metal implants which is now a technology that's taking over some of the flagship products for some of the bigger orthopedic companies. I was involved pretty heavily in not only developing 3D printing for these applications about 15 years ago, but also starting to look into some in-situ monitoring back then in the early to mid-2000s. It was a challenge and it was something that we tried to do. We stayed in touch with a lot of the regulatory bodies as we tried to evaluate and research different things, which is what we're doing right now at Onkos Surgical as well.

Erin Lanigan, Materials Engineer | EM21, Damage Tolerance Branch, Non-Destructive Evaluation Team, NASA Marshall Space Flight Center

I’m at NASA Marshall Space Flight Center in Huntsville, Alabama, on the nondestructive evaluation team. I have been supporting our efforts for NDE of additive as well as using the in-situ monitoring systems we have in-house, and developing an approach for using in-situ monitoring to help support certification. Going through the process of putting together **NASA-STD-6030** and releasing that, we had to put some thought into how we're going to use NDE to support certification. We changed the role a little bit from what it was in the Marshall standard previously so it does require the NDE standard, **NASA-STD-5009**, and certain aspects of that.

For the role of in-situ monitoring, really thinking about taking it from just process control to actually being used like an NDE technique as a quantitative indicator of part quality and what that would take. So, thinking about a proven causal correlation between what you're seeing in the monitoring data and defects in the part. Somebody mentioned earlier the rate of false positives. I would add to that just the sheer amount of data from in-situ monitoring. How we can go through all that data in a very repeatable and reliable way and pick out only those indications that actually correspond to defects in the part and get a good correlation between those. We've got a lot of work left ahead of us before we're able to put that into practice but that's the goal of how we would use that to support certification. We're doing a lot of work in-house building seeded defects, looking at them with CT and Robo-Met.3D serial sectioning so we have a good 3-dimensional view of the metallography. Figuring out which defect sizes would potentially be a concern for metallography but maybe not be visible in CT. How defects show up in-situ which, if they are seeded defects, show up very well in in-situ, but then figuring out which ones are actually going to end up in the part and which ones would be a size of concern. There are challenges of course for CT of additive. A lot of people think it's a catch-all but a lot of times you don't have a critical flaw size to work with very early on in the game. So, we're trying to find the best we can and with additive there's a lot of different types of defects and sizes of defects that can form. So, just trying to develop CT capability as well and quantify that and understand the limitations. We have a workshop that NASA Marshall put together with the ASTM AM CoE that's going to be in Huntsville on January 26th. It’s a one day in-person meeting talking about the role of in-situ monitoring, specifically looking towards that role in qualification and certification. So, using it in a production-like setting and having those aspects of correlating the monitoring data to defects in the part and looking towards using it for that function. If you're interested in that, you can go to www.amcoe.org/events or reach out to me or anyone from the CoE and we can get you the information. (Note: this meeting was postponed, looking to reschedule in late June).

Moderated Discussion

What are the components that you typically see a part of an AM product certification package or the factors you commonly encounter when you think about meeting regulatory requirements for an AM product?
(Nick) I can provide perspective on what we think about to meet the regulatory environment and not just for in-situ but for aerospace. If you look at additive or any process intensive additive manufacturing process, it's really demonstrating stability, repeatability, and reliability. How do we distill all of this knowledge and learning over the past few years to get down to a clear set of acceptance criteria that can go into a standard or specification, that has any tolerancing or any uncertainty incorporated in it? When I'm looking at additive, and process monitoring, there's just so much data. At the end of the day, we have to understand how to make this process stable and repeatable and here's what drives it. Here's how we can present data in a way that our regulatory partners get comfortable with so we can use these products safely at the end use. I think everything starts there. And then there's just a lot of specifics, whether it's sensors or data analytics. You know, really, as we're trying to expand upon that. So that's kind of where I always start from.

How does your organization approach inspection/monitoring for AM? If, like Nick said, we've got to convince our customers that what we're doing is safe, reliable, and repeatable, how does that influence your day-to-day or long-term vision for your approach to your inspection and monitoring needs?
(Patrick) Speaking for post-process inspection from the GE Aviation perspective, we view additive manufacturing the same way that we view our other manufacturing processes. It's just a different manufacturing process. Granted it may produce different types of defects than traditional manufacturing methods but, in terms of the way we design and test and ultimately go to the certification program of the part, we follow that same process for all our different manufacturing techniques. We look at additive the same way. We follow those same processes and procedures as much as possible. We may be using different inspection techniques or looking for different types of flaws compared to conventional manufacturing methods, but we really rely on our years of experience building our products and utilize that process as much as possible.

(Eric) Jumping off what Patrick described, in the development of the WK75329 standard, what we're trying to do is to gather the cumulative experience that exists in the community. We have a team that includes folks from industry, the FDA, NASA, the Department of Defense. We're trying to pull together that cumulative knowledge on what inspection methods are relevant to additive manufacturing. What we've compiled is a list that all have standard practices or specifications to back them up. They include: radiography, CT, ultrasonics, PCRT, penetrant, and visual testing. Then we consider where we want to inspect and what's the most relevant point in the process to inspect. For post-build NDE, we're really looking for inspecting the part in its condition of use. So, we understand that, if any flaws are present, how they are going to affect the part as it's actually being used. Then we define a couple of inspection levels. There's a level in the standard, what's called level 1, which is volumetric plus surface inspection. Then there's a level 2, which is surface only. We take that experience to understand what inspection level we need to designate for a particular component. Is it sufficient to just do a surface only inspection or do we need something that goes deeper into that subsurface realm? And then the cognizant engineering organizations are responsible for determining what inspection levels are required for a given part. For flaw considerations, we've accumulated a lot of knowledge where we're basing terminology and definitions of defects on established standards. There's an **ASTM E1366** standard terminology for NDE but then there's the more AM-specific which includes ASTM E3166, standard guide for NDE of aerospace metal AM parts. And then there's the ISO 52905 and 52906 standards being developed by ISO, and understanding how the flaws are relevant to AM. The workgroup has been determining what sizing criteria are appropriate. That is based on an understanding of the inspection process capability for the different methods that are listed in the standard. It's going to be based on agreement between the inspection AM supplier and all the cognizant engineering organizations that are involved.

(Gene) Just to add a little bit of commercial context from a medical device perspective, realize that for medical devices in orthopedics, in particular, a lot of the 3D printing is happening for patient-specific or customized implants. But a lot of the 3D printing is really being done on a serial basis where hundreds if not thousands of pieces are printed on a metal powder bed printer and implanted every single day. So, this has become a big commercial interest and there are a lot of costs involved. It's important to remember that whatever inspection criteria are established, they've got to be friendly from a quality perspective, and acceptable from a cost perspective. The biggest fear with a lot of these in-situ processes is what Erin mentioned, the false positives. You don't want to scrap an entire batch that's been building for 20 hours at hour 21 over something that you see in-situ, either visually, through a heat IR monitoring system, or even acoustically, and then realize maybe we should have let the pieces keep on building. So, from the medical device perspective, even in metals, this is a mass production environment that's occurring right now in orthopedics.

We sometimes talk about in-situ monitoring as if it's a standalone item but it's not. It's a necessary step that can't happen in a silo. So, how do we approach inspection and certification holistically? Are there any experiences that people have to share?

(Abdalla) We work with a variety of customers: government organizations, academics, and private corporations. The general feeling around in-situ monitoring seems to be that, perhaps for the near term, it's going to augment available post process NDE methods. For instance, we work with commercial, large aerospace companies where they have a very specific process to repair some component, and they're interested in one particular variable that's very difficult monitoring. We can work with them to define novel or customized sensors to be able to monitor that one variable with a very good degree of confidence. Ultimately, though, given the application that they're interested in, they are not going to rely solely on ourselves. They are not going to abort a build because our sensor flagged something. Maybe they will if it's something really bad. But it's going to be an additional source of information for the near term. I don't know of anyone who is so confident in the technology at this point. If you look at the NASA standard, and what Erin is saying, you have to have a causal relationship between the sensor data and the flaws, and maybe the process physics. That's not going to happen anytime soon. The only thing we can leverage to analyze such large datasets is automated machine learning. Either the standard for what's acceptable in terms of correlating sensor data to performance needs to change, or we need to have a step change in how we approach in-situ data.

(Gene) The biggest gap is really the correlation or the causality of it. You could correlate, but is it really causal? That's the big challenge. You could get a lot of information from in-situ monitoring and whatever method you use. But, at the end of the day, solid metal parts come off a machine. They almost always get processed subsequently either through hipping or some kind of heat treatment. So, you've got to really take that failure mode or that failure hazard that you might pick up with an in-situ monitoring system and then take it all the way through and see if it really did cause an issue. I think that's where the biggest gaps exist. And, frankly, it's very hard to do that. It’s a lot of money and a lot of development work to create that connection between the two. That's what challenges a lot of people. But the problem is still there. I think it will come and it's just a matter of time before people invest the right amount of time, money, and effort figuring that out, because it will pay dividends in the future. But we're not there yet. Certainly, we're still a way off in my opinion.

(Nick) I agree. Going back to the previous discussion, whether it's additive or another manufacturing process, if you're qualifying a part, you know the quality, safety, and other requirements it needs to meet. We have to use what's available now and what's been proven. The additive process monitoring or in-situ can be very complementary. If you're looking from an organizational perspective, where can you use it for very specific decision-making? Can you get acceptance criteria? Is that practical? Accelerating process development, where you have a process expert who's reviewing the data? There's a lot of value there. It can guide you in decision-making, on how to operate the equipment. Perhaps you have a root cause investigation that can lend itself to more customized analysis, because you have to answer a very specific question. And when you get all of that learning, it's very helpful. Those use cases provide a lot of benefit to folks adopting additive. But, ultimately, to get to the point where it can be distilled down into clear decision-making, especially in production, I agree, we're not there yet. Those types of use cases are going to help us get there. What can we do to accelerate our understanding of new sensors? There's a lot out there. It can take a lot of investment physically making and trying parts to understand the capability of a new in-situ sensor and how you can use it. Any way to accelerate that into a shorter timeframe in a development cycle is going to help adoption, because you don't have that sunk cost of getting to a point where maybe you can't use it for what you thought you could use it. Anything we can do to accelerate the learning is going to help. But, in the meantime, whether it's enhanced process monitoring, health monitoring of machines, there's a lot of use cases that will help industry get to that end goal potentially a little bit faster.

(Eric) Just to bring it up from the points that Gene and Nick have made, understanding the effects of the defects that we're seeing with the ins-situ tools or with post-build NDE continues to be really important. There's been some good work done on that already. There was an America Makes program out of Youngstown State University that started with Brett Conner and then Holly Martin looking at effects of defects. Sample populations in that program were examined with multiple methods and there were some in-situ data collected as well. There's a lot of great knowledge generated on effects of defects. As a community we are probably still learning from that program. Additional work along those lines would be really beneficial.

These are all vital components that play a major role in how the community overall is approaching, developing, and verifying the value of inspection, or in-situ process monitoring technologies. To take a half step back, I want to ask another fundamental question. When you hear the term in-situ monitoring, what do you think of? And then how do you feel it offers value to your products and stakeholders? We’ve heard repeatability, process self-monitoring. There are a broad range of use cases.

(Erin) We can think about a couple different categories of monitoring systems, not really strictly defined. There's a lot of systems that monitor the process such as melt pool monitoring, any camera-based systems or thermal systems (temperature sensing) that are just keeping an eye on the melt pool, versus systems that inspect between layers, camera-based systems or profilometry, or anything like that. And then another layer deeper there are systems that can only see the process as it is, either during the building process, or between layers. Then there are ones that we would call an active system in the NDE sense of it's actually putting some excitation into the part and reading a response. So, something like laser ultrasonic or X-ray in-situ, where there's interrogation of the previous build layers. In a lot of cases, especially in the ones that are monitoring the process, it's key to make that distinction. It can be challenging to make that correlation between the process signatures and the defects in the finished part. Whereas if it's actually doing NDE in-situ, then you might have a little bit more information to work with about seeing the defect as it's formed and after it's formed. I think those would end up being very different. Maybe not different approaches, but different levels of ease of actually making that correlation to finished defects

(Gene) For the medical device industry, from my perspective, it's very utilitarian. Is there something going on with the laser? Does the laser give out? Does it lose power? Is there something wrong with the powder bed as you're putting the next layer down? Are you getting splattered re-depositing or are you oxidizing something? To be able to detect that right away reliably with the ability to say this is definitely going to cause you to have a defect, which is going to be deleterious to your fatigue strength, that would be a home run. That would be absolutely fantastic. I'm not even talking about complex lattice structures. That's a whole different thing in and of itself. But if something like that could exist, that would be great. When you think about that, does that type of monitoring exist in technologies that are hundreds of years old, like casting? I don't think it does. With casting, people still pull parts out and X-ray them, or they do some kind of infiltration test. I think it exists there where you've got molten metals and it's really hard to get a good look at what's happening as the process is occurring. Maybe, comparatively speaking, additive manufacturing is already miles ahead of something like casting where scrap rates can be pretty high—five percent is considered not too bad. I think it's pretty basic, pretty utilitarian, but at least from my perspective in medical devices, for orthopedics.

(Cambre) To add something that Gene kind of said earlier from the medical device perspective, there are two schools of thought: large-scale, serialized production, and one-off, patient-specific implants. We're never going to destructively test the single implant that we're making for one specific patient. Moreover, in both the orthopedic, oncology space, and other trauma spaces, we don't have a lot of time to waste. If we're going to fail a build, we want to fail it early so we can start it again and get the implant delivered to the patient. There's also a time-based aspect in the process that we do, particularly on the patient-specific side for the medical device.

(Abdalla) I would build on those points a little bit by saying we can talk about sensors in terms of their potential use cases. In-process monitoring can be used, for instance, to do machine health monitoring or to detect systematic shifts. I would argue that's done on some machines already today. So, for instance, you can have a spot check of your laser powder every few layers. You can have a camera looking at your recoat or an accelerometer attached to your recoder blade to see if there's a significant vibration or issue there. That already exists; that's really good. That tells us something useful. The more difficult thing, which a lot of people are alluding to and trying to get to, is being able to detect local defects, meaning I have a defect in this particular location in this part. The even harder thing to reach is to be able to identify defects that matter, meaning I have a defect in this critical location and that will cause part failure. So, I think there's various levels of use cases for these in-situ sensors. The lowest hanging fruit that's available, kind of, today is machine health monitoring and looking at systematic variations in your process. I think that we can do.

I'm curious on that point. Can we have the in-situ process monitoring where we're looking at different signals or emissions coming from the processing of the materials throughout the process without machine health monitoring or do we need both?

(Abdalla) You absolutely need both. You can have one without the other. Certainly, you can do machine health monitoring without the second piece of it, if you are comfortable doing lots of NDE afterwards. If you want to get to the point where your in-situ data can honestly replace or significantly augment your NDE, which is sort of everybody's end goal, hopefully, you need both. The reason you need both is when we, for instance, use our machine learning tools to be able to figure out if there's potentially a correlation between a spectrometer blip and a flaw that we observe via CT. It's very clumsy to intake your signals and put them into a black box to get an output. What you really need to do is force these complicated and opaque algorithms to take into account the content. So, what we like to do is feed in things like, what's your actual path time? What's your laser power? What's your travel speed? If those things are systematically varied throughout your build, it becomes very difficult to make sense of your sensor signature. If for nothing else than to provide context, for the in-situ monitoring, high speed sort of emissions that you're able to detect, you really need to have a baseline for your process inputs and, better yet, you need to have a way to monitor those process inputs throughout the builds.

Are the range of standards or draft work items today defining or aligning to what you just said, Abdallah, where we need to understand the context in which these sensor signals are being produced in order to build

out the necessary knowledge base to make a decision upon? Are we being intentional in what we're developing right now to include that type of information?
(Abdalla) I'll briefly say that there are some good standards that have come out. ASTM has one of the recent standards talking about your machine configuration prior to a build. They don't have any sort of new details beyond maybe some gas flow monitoring stuff, but they point to the ISO standard on looking at your laser profile, for instance. They don't directly deal with your point about do we have a standard that says you should monitor these process inputs throughout your build, but they at least establish what your machine condition ought to be at the beginning of your build. There are some missing pieces, obviously. I haven't seen a lot of standards around, for example, powder bed fusion, your Galvanometer calibration, which is very critical. Gas flow—there's some work out there, but it's still pretty nebulous. There's lots of work to do still, but there's at least some foundational standards starting to come out.

In terms of talking about the relative maturity of our ability to conduct process health monitoring, you mentioned understanding gas flow variation, the capability of the laser, the actual power. Are there draft standards or existing standards in this space? I'll put it to the panel: do we all agree that we need these things? Because that's what AMSC is all about. If we don't have it, let's get it on the list.
(Nick) All these standards are important. In addition to individual elements of how do we standardize data collection, is standardizing how the data's pulled from the different machines. You can spend a lot of time within each specific platform, whatever vendor you're working with. There're slightly different configurations of data. We start asking some of these other questions that were brought up: calibration, validation, sensor type. One fundamental piece is whether there is a way of standardizing how the data is pulled and integrated, so you can do common analysis across platforms. In addition to some of the technical standards on repeatability needs, standards are critical for all those reasons because the more consistency we have in accessing data and understanding data, the faster we are able to move.

That's a great point. Are there standards being developed that outline the necessary components to what we all coin process health monitoring?
(Patrick) I'm not aware of any being developed within ASTM. ASTM is coming out with a Standard Guide for in-process monitoring which would be a first step towards building Standard Practice documents. Having the guide that baselines and defines terminology, defines the different in-process monitoring methods that people can refer to, will enable the building of more detailed Standard Practices based on that common terminology. That's one thing we've struggled with in the industry—establishing that common terminology. The machine side of the industry is a little bit further ahead than the NDT and the in-process monitoring side in that respect. Certainly, we've made great strides in the last couple of years, and understanding terminology in the whole space will allow us to develop those standards going forward.

This hits on something Abdalla said this morning. We need to understand the processing conditions. Abdalla, you did some great work with America Makes a couple years back that's still paying dividends. What's the challenge? I was part of a workshop at the end of 2019 where data management came up there too. Why isn't this solved? How can standards help?
(Abdalla) In some parts it is solved, meaning that if you give me a certain machine, we have the expertise to connect our sensors to pull information on what the scanner is doing, what the lasers doing, what the additional sensors on that machine do, whether the manufacturer wants us to be able to have that capability or not. And the reason we can do that so easily is because most folks in the industry use very similar components. Certain scanners have been around for years and people know how to build systems around them. We can go in and intercept all that data using a man-in-the-middle type approach. We've done it and it's straightforward. That level of information is incredibly useful and we can automatically pull it and stick it into our databases. Some of the more difficult information to pull that folks consider proprietary is, for instance, the input build plan and input parameters. In order to get that information, you really have to work with the system manufacturers and the OEM. It's not a technical challenge; it's more of an IP challenge. Do folks want to share that with you or not? We've built relationships with certain entities that have allowed us to gain that information. And without that, frankly, a lot of our in-situ monitoring work would have been significantly hampered. That's in the powder bed

fusion space. In the directed energy deposition space, things are much more open. You typically have access to your build plans and you're able to easily interface your systems with sensors, and control systems, et cetera. What would be really great is to be able to have the end user potentially generate and own that IP. These commercial aerospace OEMs are in a fairly tough situation, whether they know it or not, which is they don't own the IP for the part that they're generating. They might think they do, but just because you have your design and your build plan doesn't mean you actually know how your part was built. You can lock down your machine but what happens ten or twenty years from now. You don't own the IP that you think you do. I think that's a challenge in dealing with the commercial system manufacturers today that one has to be cognizant of.

(Nick) Certainly, if you look across platforms and at various expertise across industries, you can pull that information today. Where standards or protocols could help is where you might be a small business and don't have that expertise. The more we can put that into common frameworks, structures, or data would help. It is an IP thing and people have to be willing to open up and sign up to standard. If you don't have that expertise but want access to that data to do a similar analysis, it might help a smaller business that wants to leverage additive and grow a little bit quicker. So, I definitely agree with Abdalla. I think there's ways standards can certainly help.

(Patrick) On the NDT side, we struggled with proprietary data for years where in the past every vendor had their own proprietary format. The NDT industry came together through ASTM and defined a common data format. But it really wasn't until the industry got together and started requiring the ASTM format for purchasing equipment to ensure open access to the data going forward, that the industry really started to see the equipment vendors move away from proprietary methods of transmitting and storing data, be it post-process inspection data or intermediate process data. That is the power of defining a standard—to open up access to the data and facilitate access to that data in a standard way across all the different platforms of interest. It's really defining the way you want to see that data as an industry group and then going to the equipment manufacturers and saying, we really want you to move in this concerted direction. It was when we finally got that kind of orchestration across the NDT industry that we started to see some progress.

(Erin) Thinking about the causal correlation of indications to defects, if you have multiple sensors that can tell what was happening with the process in more detail, you have a lot better chance of doing that. And that can be machine health process monitoring type sensors that are just reporting what the machine itself is doing. I would say there's some commercial AM OEMs that are trying to report out and record that information, and some that are not really trying to do that as a standard part of their process at all. But any standardization of that would be really helpful—trying to encourage laser powder bed fusion OEMs to record and report out machine operating basic information. Or more available standardized sets of sensors that can be put in, like the middleman role that Abdalla said, would be really good to have standardized so you have that as a baseline of what the process did and then your other monitoring data can supplement that.

These are all great considerations. I've heard common data package again and again but some of it definitely just clicked for me. The context you put it in, Patrick, helps me to understand. Not all of us know the history or appreciate the perspective. I'm also hearing that there's a lot of layers to the onion. While we get the sensor data, being able to understand the cause and effect, as Erin said it very well. There's a lot of surrounding data that we need in order to make that effective interrogation as to what may be driving the consequence that we're faced with. Very interesting. We have a couple of questions that just came in on the chat. The first says colleagues and I have seen that the pixel size in the detectors of some in-situ methods limit the max defect size that can be detected. Does the panel agree that the effective pixel size is important? If yes, do we think pixel size will reduce?

(Abdalla) It's a problem. We can talk about two different things. We can talk about in-situ sensors, or even the pixel size for something like a CT system for NDE. Both have the same kind of issue, which is we're going to larger and larger systems. So, for instance, if you're talking about going from a 250 millimeter by 250 millimeter build plate, or a 500 millimeter by 500 millimeter build plate as some system manufacturers are going to, you have to square the number of pixels to keep up with that. What if you need to put something like a camera system in your machine to monitor the layer by layer stuff? That becomes very challenging. You can take the idea of using higher resolution cameras, or you can use multiple cameras. It becomes difficult to see a scenario that's very scalable as your part sizes increase. Some other sensing modalities aren't quite so limited. For instance, if you have something like a photo diodes-based sensor that's coaxial to your laser—it is very common these days to buy a machine with that or you can make one yourself—that is no longer limited by that pixel size. It's limited by how quickly you can sample the data. You can get very fine resolution on the order of 20 micron with those types of coaxial sensors. On the NDE side, you have a very similar issue where, as the part size increases, it becomes harder to do radiography or CT scanning on these parts. One challenge is to find scalable means to be able to detect and inspect defects within your part. And, of course, your effective pixel size is always going to limit the size of the flaw that you're able to search.

(Nick) We're looking at cause and effect. If you have a certain pixel size with in-situ methods, you're trying to compare it to something else—whether it's CT or some other dataset—you're going to be limited by the least resolution of whatever that dataset is. It comes down to what does the in-situ resolution need to be. If it's a bottleneck, and you can get higher accuracy by comparing to other know truths by some other method, maybe the investment's there. But it comes down to where does the accuracy need to be. I have similar thoughts on the modalities. If you're looking at high frequency, single node, light intensity, there's options. If you're looking at image-based or some other dataset, where you're trying to turn pixels into voxels, it really becomes complicated. It comes down to what you really need, and it's going to get a lot more expensive. Is it holistically going to solve your problem? You might have another area in your process chain with lower resolution, so you may not be gaining much out of it, depending on other things you're comparing to.

We've heard a lot over the years at America Makes in particular about a desire to understand cost drivers. Are there standards, or is there a need for standard approaches and considerations to understanding cost drivers, or cost modeling for inspection for product certification?

(Patrick) There's certainly a need to have design engineers understand post-process inspection costs. With all the design freedoms that additive manufacturing gives design engineers, they can create some shapes that inspection engineers haven't seen before and that can be rather difficult to inspect. Inspection costs can be a big part of the business case to decide to go ahead with additive for a particular part. So that's something we're considering pretty heavily here at GE. How do we model all aspects of the additive manufacturing process when considering the business case for going additive? Certainly, inspection is a process where the industry as a whole and GE haven't done as much work in the area of cost modeling as we have in some other parts of the additive process.

(Cambre) From a small business perspective, this is something that we're painfully aware of day in and day out. I think it was Nick earlier that was talking about when you don't have an additive SME in some of these spaces, like in-situ monitoring. It's a little bit of a puzzle for us to decide is that something that we want to invest both resources and time of our engineering team into, as well as looking to bring on that expertise. That's certainly something that would be valuable as we see more small and medium sized businesses that are looking to move from destructive evaluation methods to nondestructive methods or in-situ methods, to move upstream in our monitoring and inspection processes. But we have to understand where is our ROI going to be and are we going to break even or come out ahead on those processes if we make the investment.

(Nick) I haven't come across standards to answer that. We know additive is so part-specific and when it comes down to cost, how do we tackle that? Whether it's inspection or machining or whatnot, where you have all these unique part-specific things can be big cost drivers. There's a lot of best practices that you need to incorporate. I think there's some research on complexity. If you have enough data, can you get close on an estimate? It would be interesting. I'm not seeing a lot of standards or other approaches to estimate the cost of an AM part and provide a systematic way to get there. A lot of it is building up internal capability with best practices, so you're not missing something.

Speaking about trying to be able to kind of short circuit the development cycle to better and more quickly realize return on investment, are there merits – we heard a lot about probability of detection (POD) this

morning – are there merits to standard methods for doing this? Because I don't think everyone in the supply chain understands how to do it or do it to the point where they're going to satisfy their customer base.
(Nick) In aerospace, we have mission critical applications. If you want to go from process monitoring, you need probabilities of detection for end use. If there's ways of accelerating, it's critical. It kind of goes back to my initial comment, how do you rapidly assess the sensor capability so you want to invest in it? And then how do you rapidly do a POD with best practices so you can get a curve that an engineer can utilize.

Is the reason we don't have standard guidance because it's more technique than method, or is it just that we don't have a documented method that we're all able to share just yet?
(Erin) I think it's that second one. Even in NDE, where probability of detection is used, there's not a lot of common knowledge about how to do it. There are different standards that people follow to try to implement that. But thinking about adapting POD to in-situ monitoring, you really need that correlation of detecting something that's going to matter. Like Abdalla mentioned, we don't really have that causal correlation now. So, I think a lack of having that process defined, and being at a level where it's being done in practice, is the main reason we don't have standards yet. But having standardized processes for making those correlations for determining what's important for effects of defects, the more we can build up that body of knowledge in ways that are public and shareable, is going to be really helpful for everyone.

(Gene) One of the challenges is that every part is different. Not only is every part different, every machine is different. Even the same machines or the same models coming from the same manufacturer. Sometimes you've got a sweet spot in machine A and you've got a different sweet spot in machine B and you don't know why that is. Is it the gas flow issue? Is there something subtly different about the design which messes with the fluid dynamics of the gas? That kind of confounds things. You've really got this confluence of a bunch of different variables. That confuses a lot of people and makes standardization even more difficult. What do you do with this machine that has got some weird anomaly going on? Do you just discount it from your standard data set that you're trying to collect? I don't know. Something else that I've seen with production partners that we work with.

Earlier in my career, I would talk to the qualified engineer technician doing the NDE work and I'd hear, 3/16 flat bottom hole. I don't think we have a 3/16 flat bottom hole standard for AM. I think that builds upon 50 years of understanding material behavior, like the mechanical properties to say that a 3/16 flat bottom hole is what I need. Is it that we need to do more mechanical testing before we get there or how do we get there from here? When I hear probability of detection, I'm thinking I've got to drill a hole and then make sure I can detect that hole. But right now, we're saying, who cares. I don't even know how big the hole should be that we need to get to that critical flaw because I don't understand the mechanical behavior of this material. Is that the problem, which is the chicken and the egg?
(Abdalla) There's multiple layers of issues here. In terms of the critical flaw sizes, one of the big issues is how do you reliably generate a particular flaw type, so that you can understand how to detect it and how to generate mechanical property data that identifies what the effect of a particular flaw size is. What I would say, and this is might be controversial, is that there are bad ways to do that. The bad way to do that is to put a hole in your CAD file and print. I understand there are standards being developed around that concept. In my personal opinion, that is a terrible technique for a number of reasons. One is that you don't actually know what the machine is going to do with that void. Some machines will try to insert an internal contour. Some won't. Some will actually ignore that hole altogether and just say, if it's below a certain size, it's not really meant to be there. There's a disconnect between that technique and what the machine is actually doing in reality, what the laser and the scanner are actually doing. There are other methods that we've used essentially to do that, which is to control at the laser level, essentially force the laser pallet off for 20 to 100 microseconds over the particular region. But that also has its downside. We've tried to implement techniques like take an automated XY state system, move it to a particular position, drop a particle at a known position, and then scan over to try to insert that data. That's also not that great The best way to do it potentially is to just build tens to hundreds to thousands of parts and let nature dictate where the flaws are, then figure out how to identify and inspect those flaws, and then do very rigorous mechanical testing. But that’s very expensive. A research organization like ours can't do that.

Perhaps an OEM that's doing serial production of these components over a dozen years can establish that database. But there's a fundamental research question, which is how would you generate a particular set of flaws that are representative of real flaws? We have an America Makes program that's attempting to address that. We're getting fatigue data now and hopefully we can convince the community that it's relevant. But I think there's going to be some debate for some period of time about how do you create flaws that are representative of real flaws. Only when you have something like that, can you start talking about establishing probability of detection, making some real strong correlations, or establishing relationships between flaw and morphology, size, location, and mechanical performance, particularly for things like fatigue.

There's a question that came in from Ben Dutton in the chat. It asks if one of the major issues is that the process is not fully understood, we don't have full control, and we can generate defects on command. I think you were just hitting upon that. But the core of this seems to be, do you think that more process modeling would help expedite our understanding?

(Eric) I think the answer is absolutely. I think process modeling that gives you an accurate physics-based understanding of the process, but could also be related to the physics of the sensors you're using in an in-situ case. If you can combine that process model with simulation of the laser UT excitation, or the infrared signal you would get from the melt pool, that will give you a much better understanding of how your in-situ sensing and the process variations correlate to each other. Similarly, if the process model can generate a physics-based simulation of the part that can then be used in a post-build NDE simulation, you get additional value from it. This is an area that Vibrant is working on heavily, simulating the effects of material state variations in AM parts. But the same approach could be used for other NDE methods, like CT, ultrasonic, etc. If your process model gives you that accurate physics-based simulation, you can simulate the UT excitation or the resonance excitation or the CT scan and get a much better understanding of how all these things relate to each other. The biggest challenge in that approach is having a way to verify and validate your model and make sure that that model is producing something that is physically accurate. That's something that probably needs more work.

You brought up an excellent point. This came up in the FAA EASA workshop a few weeks ago. This idea of modeling to aid in effective NDE. You brought up that there's a lot of physics behind all this. But we don't have a lot of standards for modeling, even effective means of doing validation. It gets back to method and technique again. Are there opportunities here? Where do we all think the value is? How can we develop more standard approaches to this?

(Abdalla) We work with lots of folks who do process modeling. Quite honestly, there are various levels. It would be very useful to have a method to be able to predict a sensor response based on the physics. That's reasonably doable. The difficulty with process monitoring and powder bed fusion is that it's an incredibly complicated process. You have different scales of models. You have the Lawrence Livermore type models, which are insanely complicated. They have a user sort of facility type approach now where you can buy hours to work with their model. But even that level of sophisticated model only knows the physics that you input into the model. We think we understand some of the fundamental concepts, but there are some things that are very difficult to model and are not incorporated in their numerical methods. In terms of developing a standard for model validation, or for a use of a model, that would be very difficult because it's a complicated problem. You can figure out maybe a reasonable approach to do it, but the physics in some cases, even if they're kind of known, are very difficult to incorporate. You're dealing with complicated melt flows and an insane number of thermal physical properties that you kind of know, but not really—that you're guessing about. When we talk about using models to accelerate process understanding or accelerate the use of in-situ monitoring, we have to be fairly careful about how we scope that model and recognize that the model knows the physics that you input into that model. It's not going to predict something new, because it only knows what you tell it.

(Gene) That's a great point. I think it was Patrick who said that additive manufacturing is just another manufacturing process. And that's the way it should be treated. But let's admit it is one of the more complex manufacturing processes that's been around in the last 100 years. Not only are the physics and the flow dynamics and the kinetics complex, the metallurgy, the metallography, is crazy. We're building stuff off the machine that has no explainable metallurgy to it. Or the metallurgy is just wacky. You're flash quenching some of these structures and they're not amorphous, but they're certainly hard to analyze. I think that complicates the modeling even more. If you're getting down into residual stress analysis and things like that, I presume this would be a concern. There're not many big companies out there that are doing modeling or selling modeling packages, but I imagine they would be probably quite protective of some of that software. For them to open up to having some of it standardized, I could see them being very defensive about that.

(Nick) Going back to some of my earlier engineering doing finite element methods, if you look at the range of packages, usually they're broken down into a unit or validation test where you're trying to take all the complex finite element methods that are incorporated in the code and you're trying to do some closed-form solution. Maybe heat transfer as a conduction problem where it's a closed-form, but you're breaking that down into a very specific unit test. Can I reproduce a very specific condition that is accepted across industry through closed-form? Similarly, additive is so complex and we're still learning interactions. Is there a way of breaking it down to the unit tests? Not just for model validation, but even some of the sensor work where you break it down into the right sub series of questions? I don't know how we would do that right now. But whether it's model or sensor work, you have that kind of a challenge problem too. We have a lot of work to do in this area. I think the complexity makes it hard, but is there a benchmark or a unit test that helps us add some structure to it?

We have a similar question in the chat. We started talking about some of it because we were talking about probability of detection. Trying to understand low volume production, more than one build, for example. To the point that Nick just made, just something so simple as standard calibration methods, or an ability to be able to compare one sensor to another, or one sensor modality to another, or one machine to another, or whatever. Are there opportunities there?

(Erin) That's a little tricky thinking about standardizing monitoring calibrations just because there are so many different types of monitoring systems, and how they're calibrated would be pretty specific to the developer of that system, or the type of sensor they're using. But we have an approach for comparing machines for the NASA certification approach to develop a qualified material process (QMP). And then you can do basically a sub-QMP where you repeat some of those same tests to verify that this one completed these builds and had the same things fulfilled as the other one. We can treat them as both being qualified and ready to build. There could be something like that. How you do the calibrations would depend on the manufacturer specifications, but some standard build or standard measurements to determine these systems are both within the same calibration. And, so, these monitoring systems can be compared to each other, and a POD developed for one would be okay to use for the other.

(Nick) I would echo that, at the end of the day, you have five of the same platform type, or let's say one of multiple platform types. You're trying to measure powder bed temperature, chamber temperature, what have you. As you get smarter and smarter with the machine and understand it, you learn the nuances of how it works. As we keep zooming in, at some point the sensor becomes a black box if you don't have certs, or how it's capturing what's the accuracy of the temperature and things that you may need to know as an engineer. That comes down to data access. I'm not sure where standards play but, within a fleet of 100 machines or 10 different OEMs with a powder bed technology, how do we have a level playing field to say, if I'm measuring temperature on all of them, it's the same measure, and I can relate one to the other? That's a need. Is there an element of that from a standard? Is there an element of that for equivalency? A model is as good as its input and if you don't understand the inputs, it's going to be hard to convince that correlation there, if you're going to have that variability there.

(Abdalla) Just building off of Nick and Erin's point a little bit, if you have a sensor that's intended to measure something physical, like temperature, there are some nice standards out there on how to do that prior to powder bed fusion. So, that you can kind of wrap your arms around and figure out how to solve. It's an incredibly difficult calibration to perform with a camera on a powder bed. We can certainly work on ways to integrate that into a broader standard for AM. The difficulty comes when you have sensors where it's not potentially a physical quantity. I see this happening a lot of times with photo diodes-based sensors, both that we make or that we try to do research on, as well as all these photo diodes that are on commercial sensors today. They don't report a physical metric; they report volts or they report counts, or something along those lines that’s really an arbitrary unit. Each manufacturer develops their own in-house calibration reports. For instance, when we have our coaxial photo diodes that we've designed to filter on certain wavelength, we have our own little calibration procedure that we go through to convince ourselves that it's consistent from machine to machine etc. Standardizing that without having intimate knowledge of what the sensor is supposed to do and how it's configured becomes an almost impossible task. There might be a means to turn that part over to the manufacturer to define some sort of probability of detection. I don't care how your sensor works. I just need you to demonstrate that you can detect a defect of this size using this type of machine and this type of material. That's another push that becomes very difficult as well.

Do you think that's an opportunity then? I think back to days when I was in steel and we would use inductively coupled plasma and we'd have our NIST reference standard. Is that an opportunity for folks like NIST or others to start saying this is going to be a standard emission source by which we can all baseline and benchmark and we'll have a NIST traceable reference standard to do these things? Is that what's needed here or is that overkill?
(Abdalla) For physical units, that's difficult but within the realm of possibility. For something like measuring powder bed temperature between a range of, say, 150 C to 500 C, yes, I think they can do that. If there's enough resources of interest to do that. For the more nebulous custom sensors, that becomes very difficult.

We had another question in the chat earlier when we were talking about data. It says, who is the controlling authority in additive that would implement a data storage standard, ASTM, ASME, mil standard? I know NIST has worked on a common data dictionary. I think that's at a point where that's a work item with ASTM but I don't know about others. I know ASME has done a lot in terms of product definition and product models and callouts that help in the design world. Are there others?
(Nick) What you mentioned there, Brandon, that's kind of my awareness but I’d be curious if there's others.

A lot of good topics came up this morning. There's a lot of considerations here as you go through the workflow to think about in-situ monitoring inspection. But what did you not hear this morning that you were hoping to hear? I know we haven't talked a lot about polymers or ceramics or composites. Were there things that were missing in this conversation that we need to address?
(Cambre) A lot of this conversation has been directed at PBF, but a lot of what we do in the medical device space and personalized implants is surgical cutting guides. We're doing a lot of that in different polymer systems. How do we translate the knowledge that we've been building here on some of the larger production PBF systems to some of the lower cost SLS, SLA, or DLP systems that we might be using for various surgical instruments? That's a big ask from my perspective. I don't have the answers, but I’d love somebody to help us figure it out.

So, are your needs there more like metrology, or microstructural integrity at a smaller length scale? What guides your analysis in those use cases?
(Cambre) Yeah, a lot of it is metrology, looking at surface inspection, trying to make sure that the mating anatomic surface is going to match what we intended it to be. But there are also some considerations around actual functional surgical tools that we need to be thinking about as well, more than just surface mating. This may be putting the cart before the horse, but I think somebody's going to crack the materials problem for some of the resin-based systems in, hopefully, the not-too-distant future. And then we're going to start asking all these same questions around defects and things like that when we're talking about functional implants that are permanent medical implants. Whenever someone solves the materials problem, this will be the next problem on the list to solve to really make that a reality.

I think a lot about surface engineering. America Makes has done a lot of work over the last five years looking at fatigue and people have been thinking a lot about surface roughness and trying to measure that. I heard AMPP bring up the surface condition and its potential role in corrosion rates. Are there opportunities in terms of surface measurement roughness, metrology, where there's a greater need? I know we all struggle with

what's the metric there: RA, RV. I don't know. We'll just write them all down and see if it correlates. Is there more we could be doing there?
(Nick) I think so, Brandon. In my mind, as produced parts, where you have fatigue-loaded environments, we're doing a lot of research on that. If you have better ways of characterizing that data, and correlating it to fatigue, that's going to help industry as a whole. The other piece I wanted to emphasize was how can we be agile now that there's so many new techniques being released year after year with new sensor types? How do we evaluate those in an accelerated manner, because each one individually can be a lot of effort? How do we do that in a way that you can assess the capability and what problems you are helping to solve, without requiring lots and lots of data? I think fatigue, and fatigue impacts with surfaces, if there's ways of measuring that more directly, that would be certainly valuable to a lot of end users.

I'll give the panelists another second to think on that. We have a comment regarding data. It says that ASTM F42.08 has a plan for a data management standard guide. There's a general best practice or standards that can be found from ISO/IEC/JTC1/SC32. So, there's a response from a member of our audience regarding AM data.
(Abdalla) One thing that I think Patrick said that was really interesting to me was forcing the machine manufacturers to come to a common method or means of representing build data and how they're defining their process data. I know that there are work items and standards from ASTM around common data dictionaries, common data formats, etc. Quite honestly, I think they do miss a big thing, which is if you don't know where the vectors are located to build your part, if you don't necessarily know all the little configurations, things like what's the speed of gas across your powder bed—nobody reports that (you can have sensors that measure that, and we certainly have developed sensors and other folks have developed sensors)—if you don't know some of those fundamental things that are currently not being stored or reported, it doesn't really matter what data management standards exist, you still don't know your process. You still can't transfer your process from one machine to another machine. That's a blind spot that we have to tackle somehow. Folks like ARL aren't in a position to do that, but industry folks, users of the technology, folks like the GEs, Boeings etc., I think they're spending a lot of money buying these machines. And, so, if there's consensus in the industry around what data you need to have in order to make these machines useful, both in the short-term, and in the long-term, and in order to be able to make in-situ sensing and machine interfacing useful, that has the potential to move the ball forward in terms of driving machine manufacturers to adopt common standards and common format.

We have another question in the chat. I was hoping we could close out on needs in terms of future standards but, ultimately, the key component to that is data. We've heard that a couple of times here this afternoon. This question asks, what is required to help foster industry-wide collaboration where we can share more data that would help generate standards faster, or generate the right types of standards? Are there unexploited opportunities there? Do we feel that is a feasible means to standards development or is that kind of hard to overcome the IP hurdle?
(Gene) Maybe the question we need to ask is, are there any corollaries in any other industries? It's a great question. The feeling I've gotten dealing with manufacturers of equipment is they do want to keep things very tight to the vest. I certainly understand that, but I'm wondering how has that been developed in other manufacturing domains, casting or forging or what have you. I don't know. Does America Makes have any insight into it? Maybe that's something you guys can look into and come back to us and say, this is how it's done in this industry, that's how it's done there.

I feel the same way. We heard this a little bit today. The folks who think a lot about in-situ monitoring, maybe there's something we can learn from the folks who think a lot about NDE. A couple months ago we had a similar conversation on feedstock, and we asked folks from the welding community to come and talk. There are things we can learn from other domains that maybe we don't deal with every day. That's a great point. I'm sure everyone came here with something they were hoping to hear about, this type of standard, or this type of opportunity for standards development. Maybe, they didn't get a chance to hear about it.We'll use that as a closing point.

(Gene) Stating the obvious, standards are needed for 3D printing, especially in powder bed. Some of the stuff we deal with is certainly very complex. If there was a document we could go to or reference to say, this is going to be a defect that's going to create problems in a standard size, titanium fatigue model, then we've got to watch out for that. I don't think that exists, but, yeah, absolutely. It's certainly very desirable. The medical device industry certainly appreciates the complexity and how difficult it is, especially with 3D printing to get to that point.

Closing Remarks

- Brandon Ribic and Jim McCabe

Brandon Ribic provided his closing thoughts. Additive is a complex, multifaceted manufacturing technology. We started today's conversation talking about inspection or monitoring and then got into control theory, design, metallurgy, and material science. We included some physics either to talk about the process or the inspection technology itself. Then we introduced mechanics and cost models and all of a sudden it's the full gamut of considerations. All the things that help begat our business model success, and allow us to convince our customers this is all safe. From a technical perspective, we've mapped out the opportunity space, all the vital considerations that go into defining the utility and opportunity for monitoring and inspection technologies that pertain to additively manufactured products for a wide range of industries and applications.

Dr. Ribic and Jim McCabe expressed their appreciation for everyone's time today, thanking the speakers and audience members. These have been some great conversations that have given us a lot to think about going forward.

Mr. McCabe noted that today's event is part of an ongoing conversation that we're having trying to tie applied research back to standards needs and standards development. What's being worked on? What more is needed? There's a gaps progress report against our roadmap version 2 that came out in November. It is available at www.ansi.org/amsc. You can download that along with the original standards roadmap. We'll be sharing the presentations and a recording of today's event, and producing a written report.