2021 EASA – FAA AM
INDUSTRY – REGULATOR EVENT
(virtual meeting)

WORKING GROUP 2:
Fatigue and Damage Tolerance (F&DT) and Non-Destructive Inspection (NDI) Considerations for Metal AM

WG2 co-chairs:

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Final Briefing
Nov. 12, 2021

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WG2 – Friday (Nov. 12) De-brief for the Workshop Participants

- Summary of the WG2 key outcomes (PowerPoint)
  - B/O Sessions Highlights and Summary

    Recommendations for:

    - Future Work
    - Development of guidance content, e.g. input to SDOs work w.r.t. F&DT and NDI
    - R&D Topics (enablers for the above)

    Note: WG2 co-chairs to provide 1-2 page written summary of B/O Session #2 outcomes within 2 weeks from this Event for inclusion in the proceedings

WG#2 Description

Fatigue and damage toleration (F&DT) related qualification considerations and related certification requirements have historically presented more significant challenges for structural components produced using process-intensive manufacturing technologies, and additive manufacturing (AM) is no exception. While all the key tenets of the certification requirements apply to AM, *there is a number of material system specific considerations that need to be understood and properly accounted for*, including inherent material anomalies and their effect on fatigue life, residual stresses, non-destructive inspection (NDI) challenges, effects of post-processing, etc.

The need for developing a good understanding of these factors is further elevated by the *expected near-term introduction of high-criticality AM parts* in Civil Aviation that will be subject to F&DT regulatory requirements.

The intent of this working group is to discuss the most recent developments in these technical areas, while *building on the outcomes of the F&DT and NDI breakout sessions from the 2019 and 2020 AM Workshops*, and to further develop considerations for aviation application of AM.

The *desired outcomes* of this working group and the corresponding breakout sessions during the 2021 AM Workshop include:

A. **Formulating recommendations for standards development organizations (SDOs) / industry working groups as to which AM-specific F&DT and NDI topics should be addressed by public standards or specifications, and to develop initial technical considerations to seed such discussion**
B. **To develop recommendations for enabling R&D work (identification of specific research topics)**

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WORKING GROUP 2

WGs - development since 2020 Event (*note – breakout sessions were used since 2018 workshop*)

- **Co-chairs and Core WG Teams identified and formed in advance of the 2021 event**
- **WG2 theme is recognized as a carry-over from the 2020 event**

WG2 - Core Team (Aerospace Industry + Government)

- **10+ people supported several preparation meetings** in 2021**
- **WG2 objectives and priorities defined → *see next slide for priorities***
- **Need for *tangible outputs* recognized:**
  - **Gap Analysis**
  - ➢ **Input to SDOs and Consortia work**
  - ➢ **Input into R&D prioritization**

** **WG2 preparation meetings held in 2021: 2nd July, 24th September, 14th October, 28th October, 5th November**

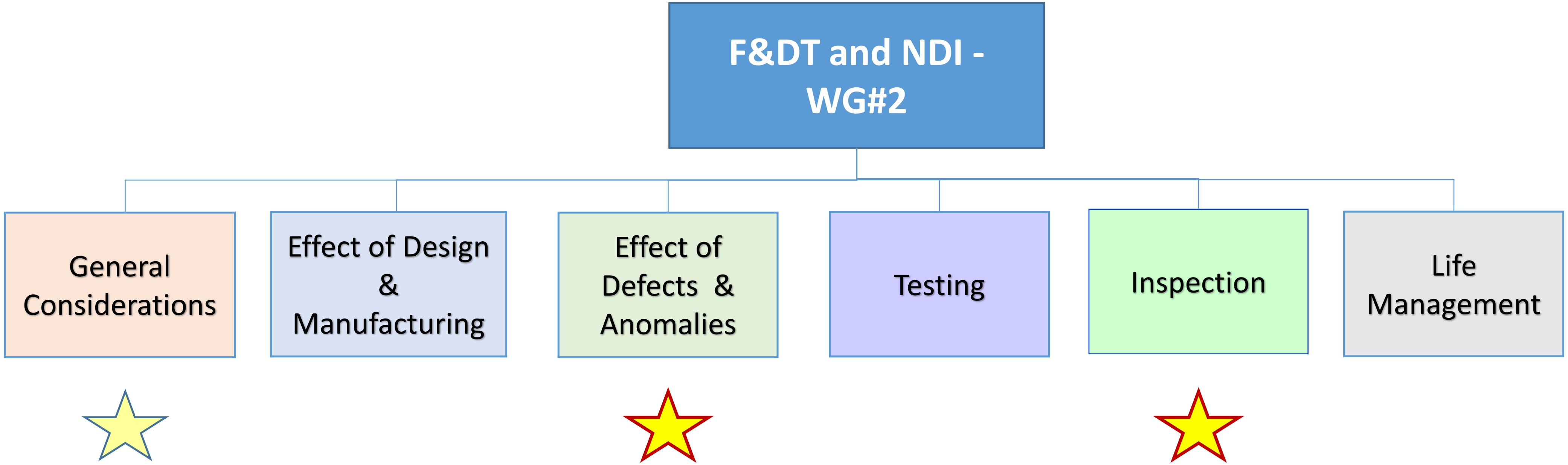
Prioritization Result from 2020 Workshop

The 2020 prioritization results ("Top 3") are still deemed relevant and will be carried forward in 2021

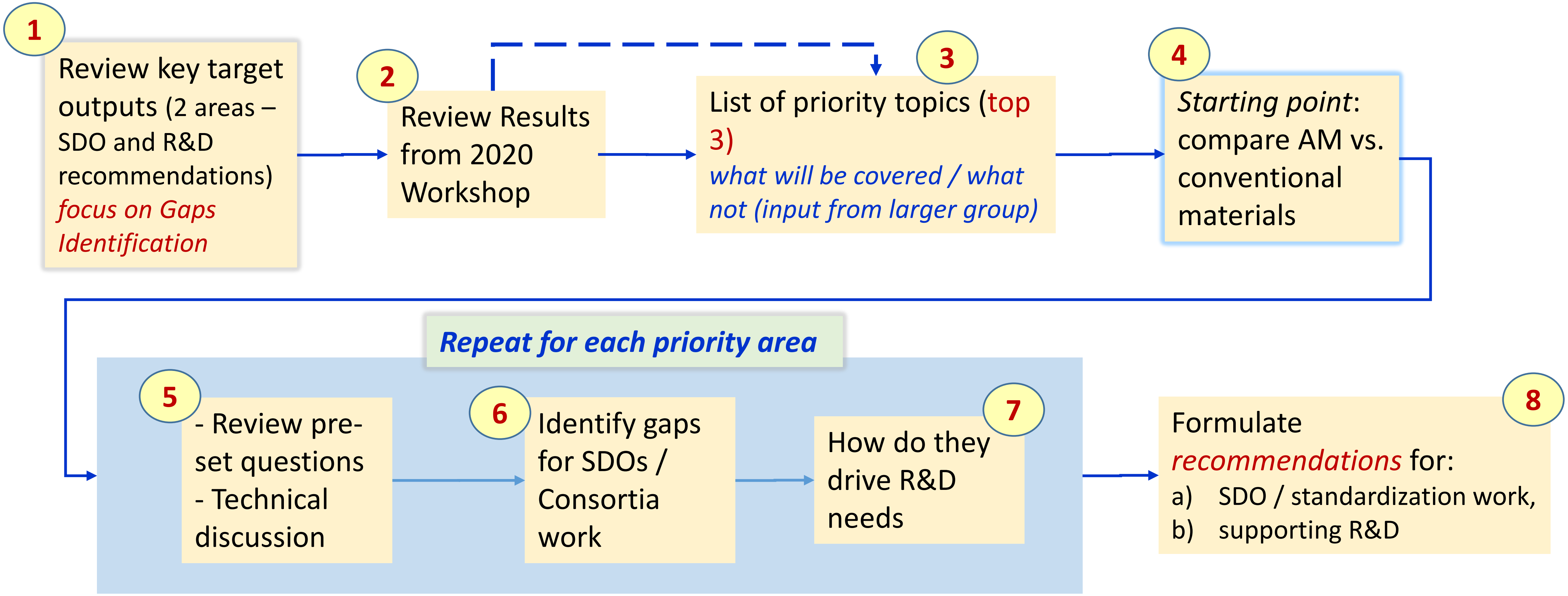
	A	B	C	D	E	F	G	H
1			**1A.Fatigue**		**1B.DT**		**2A.NDI (connected to F&DT)**	
2	What are the key Q&C technical challenges							
3	**Data availability/data generation**							
4	1.1		**a) Relevance of coupon data to part-level data**	**9**	**a) Development of defects distribution (including exceedance curves)**	**7**	a) Developmemt of POD data - point value vs. POD vs. a?	1
5	1.1		b) Generic material allowables vs. feature-based characterization (library?)	2	b) Effect of post-processing on DT (e.g. HIP -> volume defects, surface improvements -> surface integrity, RS mitigation, heat treatment -> homogeneity and anisotropy)	1	b	
6	1.1		c) Effect of post-processing on LCF (e.g. HIP -> volume defects, surface improvements -> surface integrity, RS mitigation, heat treatment -> homogeneity and anisotropy)	**3**	c) Relevance of test coupons to part properties	1	c) Develop in-process inspection POD	2
7	1.1		~~d) Relevance of test coupons to part properties~~					
8								
9	**Methods and tools**							
10	1.2		a		a) Zoning	3	**a) Selection and validation of appropriate NDI methods for given application and anomaly types**	**5**
11	1.2		b) Part family considerations	1	**b) Deterministic vs. Probabilistic Assessment (DT)**	**5**	b	
12	1.2		c		c) Conventional S-N vs. anomaly-related framework?	2	c) Effect of post-processing on NDI (e.g. HIP ->	2
13	1.2		d) Conventional S-N vs. anomaly-related framework?	2	d) Assessment of geometrically complex parts	2	d) Use NDI to help understand some of the effe	1
14	1.2		e) Assessment of geometrically complex parts	**3**	e) Effect of post-processing on DT	2	e) Develop models to predict defect effect of f	**3**
15	1.2		f) Defintion and use of "knock-down" factors for fatigu	1				
			g) Effect of post-processing on LCF (e.g. HIP ->					

11/12/2021

WG#2 Scope at a Glance



Thought Process for WG2 Breakout Sessions
(final version)



A set of questions was developed by the core WG2 to prime the discussion during the b/o sessions

	A	B	C	D	E	F	G	H	I	J
1	*Categories*						A) Fatigue			
2			A) Fatigue		C) Damage Tolerance Assessment		C) Damage Tolerance Assessment			
3			B) Data availability/data generation		B) Data availability/data generation		D) Methods and Tools		E) NDI	
4			1. Relevance of coupon data to part-level data for fatigue properties		2. Development of defects distributions (including both size distribution and frequency of occurrence - i.e *exceedance curves*)		3. Deterministic vs. Probabilistic Assessment (DT)		4. Selection and validation of appropriate NDI methods for a given application and anomaly types	
5		1.1	What is the difference and commonality between metal AM and other alloy forms relative to this topic?	2.1	What is the difference and commonality between metal AM and other alloy forms relative to this topic?	3.1	What is the difference and commonality between metal AM and other alloy forms relative to this topic?	4.1	What is the difference and commonality between metal AM and other alloy forms relative to this topic?	
6		1.2	What properties or attributes of AM need to be accounted for to predict F&DT performance?	2.2	Who should be developing these distributions - machine makers or end users? Note - as the process changes, the distributions may change.	3.2	What are the factors that would make probabilistic approach not practical? Note - deterministic approach may be conservative and sufficient in many cases.	4.2	How can surface conditions affect NDI inspectability (not just for surface inspection methods, but also UT, CT, etc.)?	
7		1.3	How to predict fatigue crack initiation locations?	2.3	Could such information be used as a part the material & process qualification? A	3.3	Would initial probabilistic assessment be helpful in defining what type of deterministic assessment is appropriate (and conservative)?	4.3	What are the most promising NDI methods for AM? Note - micro-CT is often viewed as a "golden standard", but it also has a number of limitations (artifacts coming from different thicknesses, limited material volume, scan angles, etc.).	
8		1.4	What makes the coupon properties vs. part properties different? How to eliminate these differences? If they can't be fully eleminated, how to account for such differences?	2.4	How to demonstrate that the part is consistent with the requiements? How is the industry going to replicate design values given the high level of machine and process dependency?	3.4	What is the role (and feasibility) of a "simplified" probabilistic analysis?	4.4	Should NDI methods be tuned (validated) for specific defect types?	
9		1.5	What are the considerations for designing test coupons (e.g. capture of surface vs. volumetric defects, etc.)?	2.5	What are the methods for generating defect distributions? How is information obtained from different sources (e.g. NDI, fatigue/fractography, random sectioning, etc.) can be properly combined to develop a distribution?	3.5	How realistic should the assumed inputs into probabilistic analysis be? Note - if one makes a lot of conservative assumptions about the defects distributions, it's not much different from making conservative assumptions in deterministic analysis.	4.5	NDI may depend on part shape / size / etc.	
10		1.6	Should the methods and techniques for characterizaion of the volumetric vs. surface / near-surface properties be separated into two groups?	2.6	Can defects distributions be used to establish the appropriate defect size limits (e.g. spec or drawing notes)? At what phase in Mfg process should such limits be defined (e.g. as built part, after Heat Treat, after HIP, etc.)?	3.6	What is the role of calibration for probabilistic analysis? Note - it needs to be consistent with experience (field / production / NDI finds); needs to be distinguished from validation.	4.6	What's the balance between defects prevention vs. defects detection?	
11		1.7	How effective are hollow cylindrical bars (a popular fatigue coupon configuration) at characterizing surface condition?	2.7	Should the spacing / proximity of multiple defects be considered (e.g. do we need to include defect interaction)?			4.7	Is fidelity of standard NDI methods sufficient for AM?	
12		1.8	What are the specific quantifiable attributes that need to be looked at in order to assess the degree of similarity between the test coupon and part? Are these attributes affected by the "environment" (e.g. location of parts / coupons on the build plate, proximity to adjacent parts, etc. - for PBF)?	2.8	Need to distinguish between inherent vs. rogue defects, and how each type can be properly characterized. How can rogue defects be addressed without significant field experience?			4.8	What are the key reasons for the lack of POD studies in the public domain? (for specific NDI method / specific defects type).	
13		1.9	How may the answer to part-vs-coupon properties differ by the AM process type (e.g. LPBF vs wire DED)?	2.9	What are the difference or commonalities in developing volumetric vs. surface/near-surface defect distributions (for "effect of defects" considerations?)					
14				2.10	What is the minimum inspection / characterization volume that can yield a representative defects distribution? Note - rogue defects may still need a separate consideration.					
15										

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WORKING GROUP 2

Agenda: B/O Session - Day 1 (Tuesday, November 9) – *1 hr*

- **Summary of 2020 outcomes and 2021 WG2 pre-work**
- **Discussion of the b/o sessions format**
- **3 brief (~ 10 min each) level-setting technical presentations:**
  - **Doug Wells, NASA, 'Considerations for Qualification and Certification of Un-inspectable AM Hardware'**
  - **Andreas Fischersworring-Bunk, MTU AeroEngines, 'Use of a modified IQI Standard – a way forward in NDI?'**
  - **Armando Coro, ITP Aero, 'The relevance of AM anomalies, dimensions, amounts and locations'**

Agenda: B/O Session - Day 2 (Thursday, November 11) – *4.5 hrs*

Over 50 people were in attendance

- **Agenda review**
- **Technical discussion – start with a list of pre-set questions, and start working through them (allowing time for the larger group's input) for each of the 4 main topics**

  - Includes 10-15 min at the end of each topic *to summarize recommendations* for SDOs work and supporting R&D topics → *covered in the next few slides*

Sample Breakout Session #2 Outputs

(preliminary – based on unedited working notes)

Disclaimer – the recommendations for SDOs and R&D work presented below have not been formally compared against the existing / on-going SDO and R&D efforts and documents, other than the latent knowledge of the B/O session members

Sample Outputs

Topic #1 - Relevance of coupon data to part level data

- Recommendations for SDOs / Consortia
  - Help establish methods to show equivalence between defect states and microstructure. Standard methods for determining these attributes.
  - Develop a standard specimen configuration for evaluating as-built condition (including metallographic evaluation), and detailed procedures for evaluating it. One specific area:

    * Development of test specimens for as-built coupons fatigue test.

      One option – hollow bars, no standard at the moment.
  - Guidance on the use (and role of) purpose-built coupons in both as-built condition and after some post-processing steps (HT, surface improvements, etc.).

    May need to clarify terminology: *as-built* (no HT) vs. *as-printed* (with HT) conditions.

    (no value in fatigue tests of as-built cond.)
  - Effect of coupons size on fatigue life

    Significant difference in fatigue life observed for as-printed specimens of different diameter

Sample Outputs

Topic #1 - Relevance of coupon data to part level data

- Recommendations for R&D Work
  - Explore the use of sub-size coupons extracted directly from parts (critical areas)
  - Development of small crack models for AM
  - Understanding of crack initiation vs. propagation for different morphologies / types of AM anomalies
  - Construction of Kitagawa diagrams – standardized methods (*both R&D and SDO topic*)
  - Thermal modeling to support understanding of similitude btw. coupons and parts (local / global thermal history)

Sample Outputs

Topic #2 - Development of Defect Distributions

- Recommendations for SDOs / Consortia
  - Standardized framework for defining statistical distributions and how to use them to predict scale effects; evaluation if the coupons have the same underlying distribution as parts (methods, criteria) – may include statistical hypothesis testing → *note: this may also be an R&D topic*
  - How to combine diverse sources of information (e.g. fractography, high-fidelity NDI, metallography, etc.) to develop a comprehensive anomalies distribution. Also, standardized use of information from each individual source listed above → *note: this may also be an R&D topic*
    - May need to examine not just the output of the "nominal" process, but also deviations from the process (e.g. "qualified extremes" per D. Wells presentation)
    - Review the outcomes of the WG2 2020 proceedings in this context
  - Standard methodology for how to use defects distributions once they are developed
- Recommendations for R&D Work
  - How to translate the actual 3D anomaly shape into simplified crack growth analysis shape?
  - *See above notes with R&D work references*

Sample Outputs

Topic #3 - Deterministic vs. Probabilistic Assessment (DT)

- Recommendations for SDOs / Consortia

1. Training of the work force on the use of Prob. Methods
2. Validation framework for Prob. Methods (SAE G11 topic?)
3. Guidelines for consideration on when to use PM
   – When it's appropriate / needed; what to consider when using PM.
   – When is the use of PM "allowed"? Guardrails around the use of PM.
4. Standardize methods and key elements of PM eco system (*note – not necessarily specific to AM*)
   – May be especially beneficial for new entrants into Aviation field
5. Guidance on the use of different "levels" of PM assessment, including "simplified" PM analysis (e.g. not considering variability in every single parameter)
   – Guidance on the use of sensitivity analysis as a precursor for setting up the appropriate "level" PM model
   – Note – Tier 1s may not have all the necessary information to populate inputs into PM model

- Recommendations for R&D Work
  – On-going R&D work on existing tools – to tailor them to AM (as needed)
  – Relative to Item 4 – are there PM methods that are particularly suitable for AM applications?

Sample Outputs

Topic #4 - Selection and Validation of Appropriate NDI Methods (specific to application and anomaly type)

- Recommendations for SDOs / Consortia
  - Quality indicators relative to assessment of CT detection capabilities. How to quantify NDE data coming out of CT (ref. to NIST work). Use of calibration blocks for EC and UT (unique AM considerations).
  - Need to consider NDI capabilities at three levels – process qualification / production inspection / in-service inspection
  - Acceptable methods for introducing seeded flaws (for NDI process qual and POD). → Supporting research? Work of F42 sub-committee?
  - Guidance on when certain inspection types need to be performed in the context of production cycle
  - Guidance on the use of surface NDI (e.g. FPI) for as-built surfaces; role of post-processing steps in increasing effectiveness of such methods
    - Need to be clear what we are looking for (depends on parts criticality, application, etc.)

Sample Outputs

Topic #4 - Selection and Validation of Appropriate NDI Methods (specific to application and anomaly type)

- Recommendations for R&D Work
  - Need to understand the role of in-situ monitoring in the context of future NDI environment for AM, and parts qualification
  - Need to establish POD assessment for each NDI technique for: a) different flaw types, b) different AM processes
    - * Need to verify applicability for different geometries (size, shape), surface condition, and different alloys
    - * Consider the role of MAPOD type frameworks in the above efforts
    - * The role/need of a full POD curve (POD=f(a)) vs. point-estimate (e.g. 90/95 POD)
  - Role of “global” response-based NDI methods (e.g. resonance-based methods) → go / no-go response at a part’s level
  - Acceptable methods for introducing seeded flaws (for NDI process qual. and POD)
  - On-going work on model-assisted POD development

A big Thank You to all the core WG2 members and Breakout Session #2 participants for your time, engagement and technical contributions