

Additive Manufacturing in the Context of Structural Integrity

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Behavior of Additive Manufactured
Components *(sponsored by ASTM E08)*

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Federal Aviation
Administration



Disclaimer

The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration rules interpretation or policy



Outline

- **State of Industry**
- **Challenges for AM Implementation**
- **Regulatory Perspective**
- **Lessons Learned**
- **Risk Mitigation**



What Causes Failures?



Frequency of Failure Mechanisms *)

Failure Mechanism	% Failures (Aircraft Components)
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%



*) *Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Fatigue is the Predominant Failure Mode in Service**
- **Expect this trend to continue for metallic materials**
- **Some of the most challenging requirements for new material systems are related to F&DT**



State of Industry - Today

- **Field experience for certified metal AM parts in Civil Aviation** (*in 10,000 hours*) → **zero** *)
- **Full-scale production experience for metal AM parts in Civil Aviation** (*in 10,000 parts*) → **zero** *)

*) approximate as of the end of 2015 (based on information available to presenter)

Are New “Lessons Learned” Likely..?



State of Industry (cont.)

“Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas...”

Mr. David Joyce, GE Aviation President and CEO



“We are on the cusp of a step-change in weight reduction and efficiency – producing aircraft parts which weight 30 to 55 %, while reducing raw material used by 90 % ...”

Mr. Peter Sander, Airbus



"Metal parts from some AM systems are *already on par with their cast or wrought counterparts*. As organizations qualify and certify these and other materials and processes, the industry will grow very large..."

Source: Wohlers Report 2012



"3D printing opens up new possibilities, new design space... Through the 3D printing process, you're not constrained [by] having to get a tool in to create a shape. You can create any shape you like."

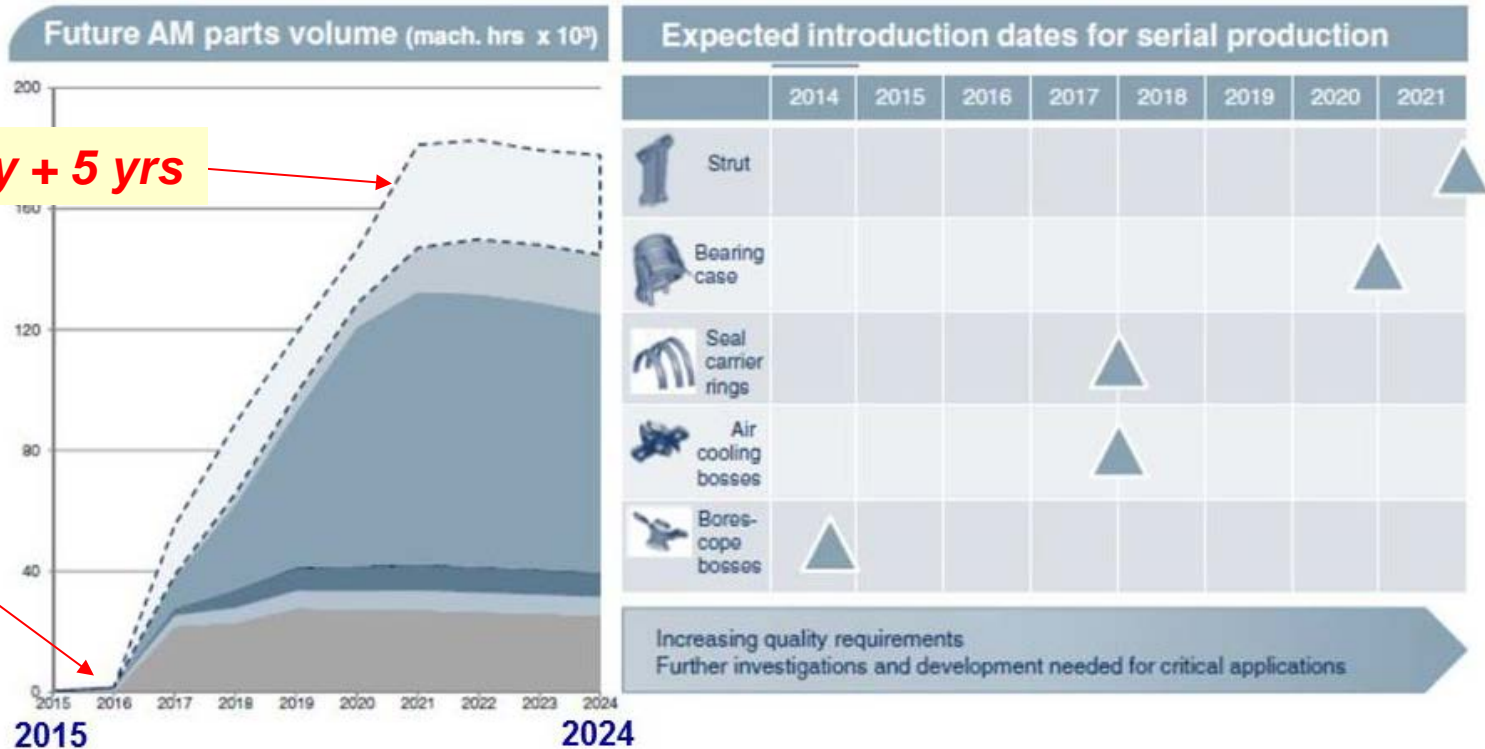
*Dr. Henner Wapenhans, Rolls-Royce
Head of Technology Strategy*



State of Industry (cont.)

Additive Manufacturing (AM) Challenges Conventional Production

Further industrialisation steps



today + 5 yrs

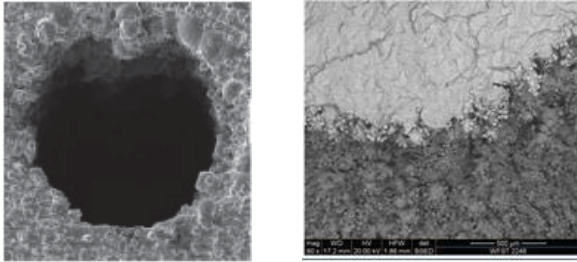
today

We are on the Cusp of a Significant Increase in the Use of Metal AM Parts in Commercial Aviation...



Federal Aviation Administration

Examples of Risk Factors for AM - Materials



Surface Quality

Powder feed rate (g/min)

Laser Power (W)

Scan speed (in/min)

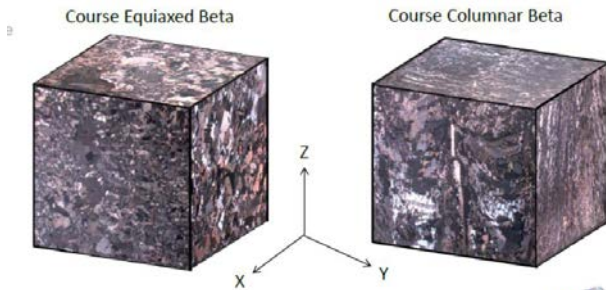
Laser spot size (in)

Substrate temp (°F)

Hatch spacing (% of calculated)

*over 100
process
parameters
identified*

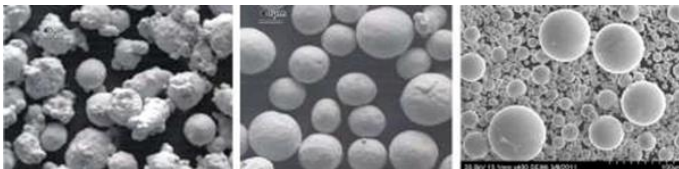
Process Controls



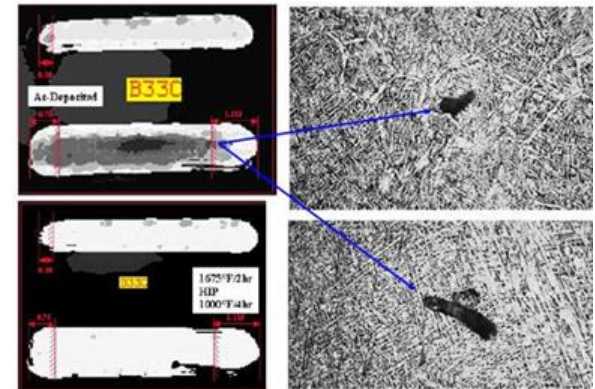
Distribution A: Approved for public release; distribution unlimited (88ABW-2015-0669)

AFRL

Microstructure Variability



Powder Control



HIP Effectiveness

Many More Identified by Experts...



Example of Risk Factors for AM - Design (Topological Optimization)

“Complexity is Free with AM...”



- **... But is it really?**
 - High number of Kt features
 - Inspectability challenges
 - Location-specific properties
 - Surface quality of hard-to-access areas
 - may need to live with as-produced surface

Need a Realistic Assessment of Technical Challenges / Risks



AM Challenges To Be Addressed

“top five”

- Limited understanding of acceptable ranges of variation for key manufacturing parameters
- Limited understanding of key failure mechanisms and material anomalies
- Lack of industry databases / allowables
- Development of capable NDI methods
- Lack of industry specs and standards

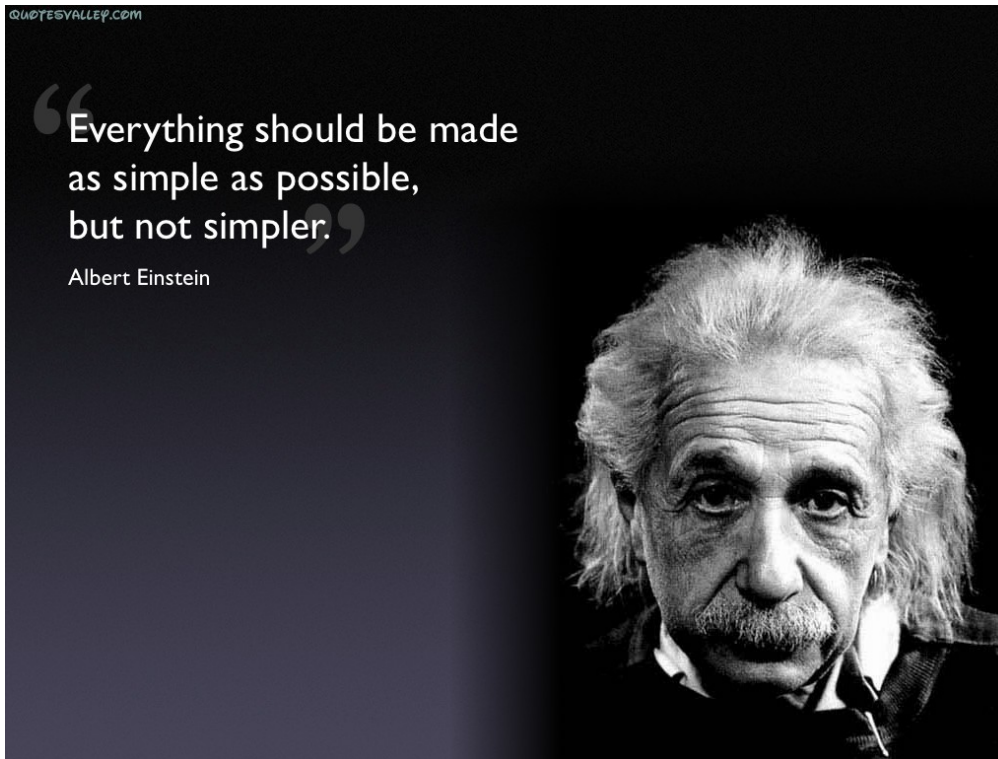
Additional level of complexity – these areas are not independent...

Other considerations

- *Lack of robust powder supply base*
- *OEM-proprietary vs. commodity type technology path*
- *Low barrier to entry for new (inexperienced?) suppliers*

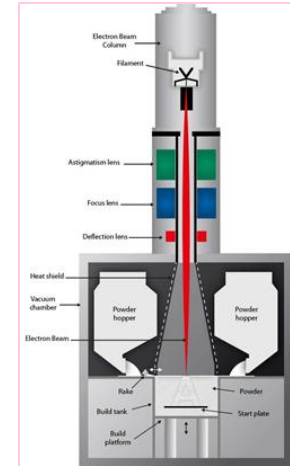
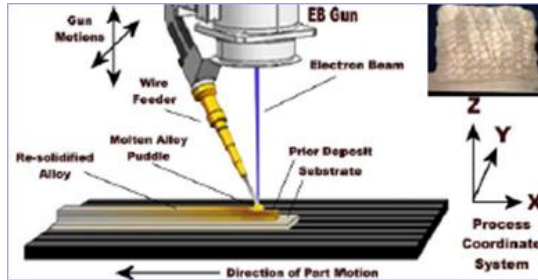


Some Regulatory Considerations for AM

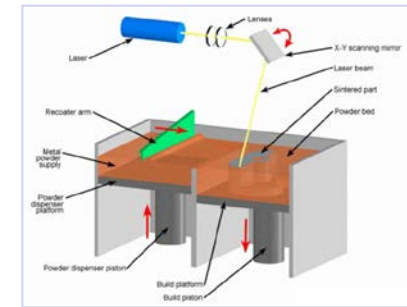


Diversity of AM Processes and Certification Domains

**By Source of Material:
Powder vs. Wire**



**By Source of Energy:
Laser vs. E-Beam**



**New Type and
Production
Certificates**

**Repair and
Overhaul
(MROs)**

**Aftermarket
Parts
(PMAs)**



Two Types of FAA Certificates for New Products (14 CFR Part 21)

- **Type Certificate**

- An applicant is issued a *Type Certificate* once they have demonstrated **through test and analysis** that the **type design data** (drawings, specifications and other documents needed to describe a design) meets all relevant regulatory requirements

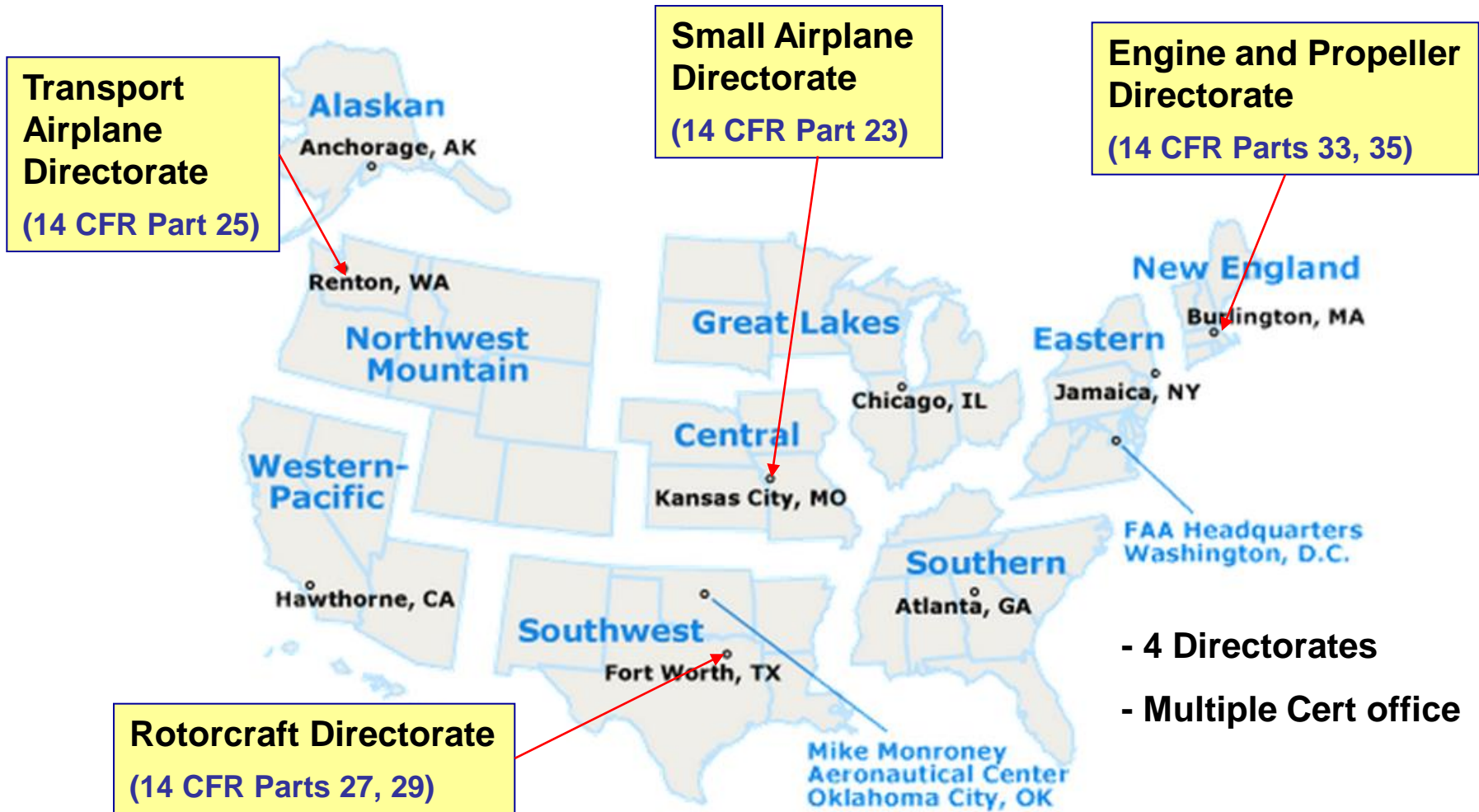
- **Production Certificate**

- An applicant is issued a *Production Certificate* once their manufacturing facilities are capable of **repeatably** producing product **per the approved Type Certificate**



Diverse Regulatory Environment

(driven by different product types)



Part Rules Comparison for Material Requirements - *General Observations*

- Detailed material related requirements are Part rule dependent
- Various levels of requirement details by Part
- *Some of the most critical material requirements (Fatigue / Damage Tolerance) are closely linked to OEMs design / analysis system, and typically approved on OEM-specific basis*



From Non-Critical to Critical

- Typical new aerospace alloy development and introduction timeline – *10 to 15 years*

➤ **However**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural components	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

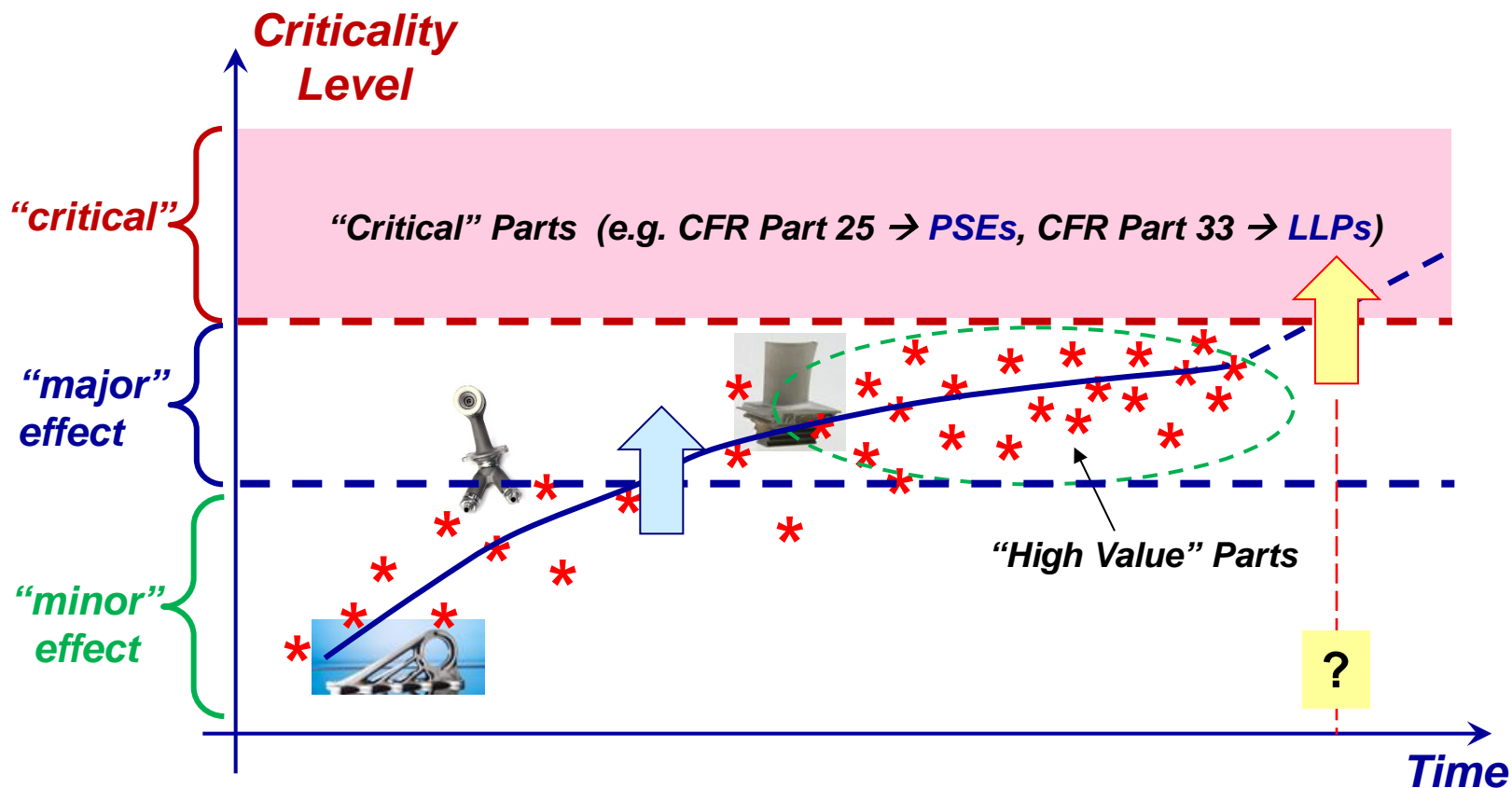
Example

“The *outcome* of Rawfeed (*an R&D program*) will be a specification for a process to additively manufacture Class 1 titanium structures, such as engine hangers, wing spars and gear ribs... expensive, critical parts...”

Reference: *Rolling Key To Additive-Manufacture Of Critical Structures*, Aviation Week & Space Technology, Nov 10, 2014.



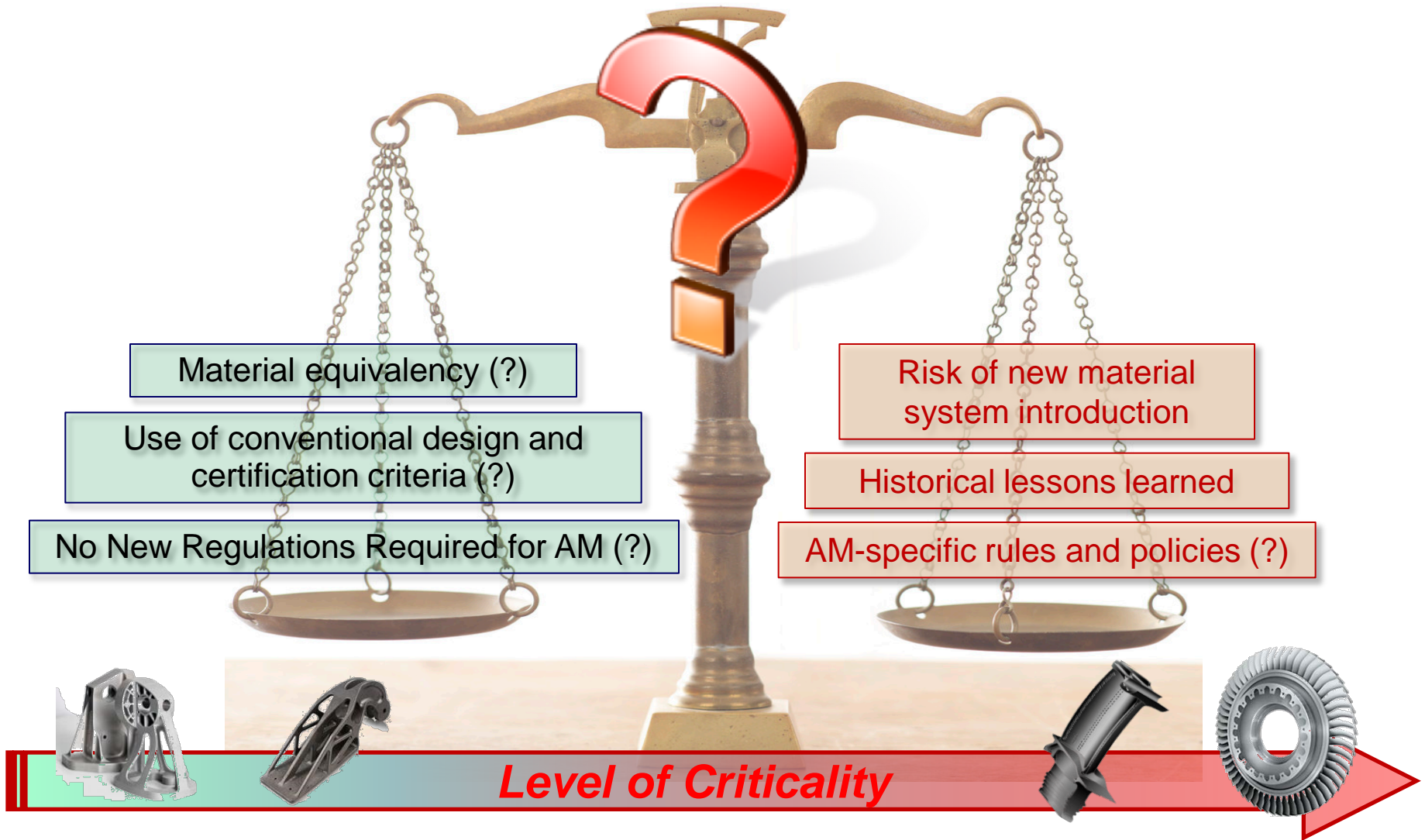
Evolution of Criticality of AM Parts



Aggregation of parts at “sub-critical” levels may result in non-trivial *cumulative* risk impact at fleet level



Finding The Right Balance...



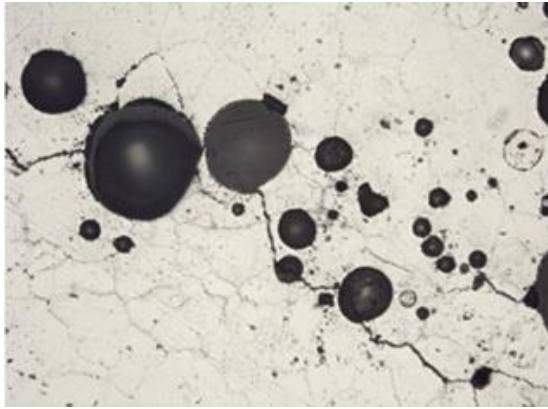
“History is a Vast Early Warning System”

Norman Cousins



Lessons Learned – Structural Castings

- Prone to manufacturing variability, material anomalies and resulting variation in material properties, including fatigue
- Range of material anomalies intrinsic to castings, including gas and shrinkage porosity, inclusions, micro-cracking etc.



Examples of Material Anomalies in Cast Alloys

Effect on debit in material properties is well documented ...*but not necessarily well quantified*



Lessons Learned – Structural Castings (cont.)

- Historically, and in part due to the *lack of modeling capabilities*, an *empirical framework* was developed to mitigate the risk of the above factors
- It consists of the following key elements:
 - **Class of Casting** (1 through 4) - determined by application criticality
 - **Casting Grade** (A through D) - defines acceptable levels of NDI indications, either for the entire part or for a specified area (zone)
 - **Casting Factor** - a safety factor originating from uncertainties in material properties

5.2.1 “... *The application of factors of safety to castings is based on the fact that the casting process can be inconsistent ...*”

5.2.2 “... *Since the mechanical properties of a casting depend on the casting design, the design values established ... for one casting might not be applicable to another casting made to the same specification.*”

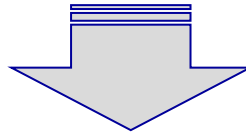
Reference: FAA Advisory Circular 25.621-1 “Casting Factors”, Oct. 2014.



Lessons Learned – Structural Castings (cont.)

Challenges

- Empirical – effects of material anomalies are not well understood or quantified → *no explicit feedback loop to process controls and QA*
- No means to assess / quantify risk
- May be too conservative in a number of cases



“...by taking every deleterious variable imaginable, it was found that average strengths were still well above minimum requirements...”

Reference: “Modern Castings”, D. McLellan, ISSN: 0026-7562, May 1994.



Lessons Learned – Powder Metallurgy (PM)

- “The early years of P/M superalloys were ones of great expectations
 - For example, in 1971 it was suggested that in 5 years, 20 to 25 % of the weight of advanced engines would be P/M superalloys...
- The application of **powder metallurgy (P/M)** to superalloys was initiated in order to overcome difficulty encountered during forging and heat treating of advanced, highly alloyed, nickel-base superalloys.
- Several major OEMs were developing this technology for 10-15 years, prior to initial applications

Reference: “P/M Superalloys – A Troubled Adolescent?”, R. L. Dreshfield and H. R. Gray, NASA Technical Memorandum 83623, 1984.



Lessons Learned – Powder Metallurgy (PM)

FLIGHT INTERNATIONAL, 11 October, 1980, pg 1413

... The US Navy grounded its 13 F-18s following the crash of a TF-18 in England on September 8 (see Flight, September 20, page 1177), following an inflight failure of one General Electric F404 engine. **The cause of the accident was the disintegration of the low-pressure turbine (LPT) disc in the right-hand (No 2) engine.**

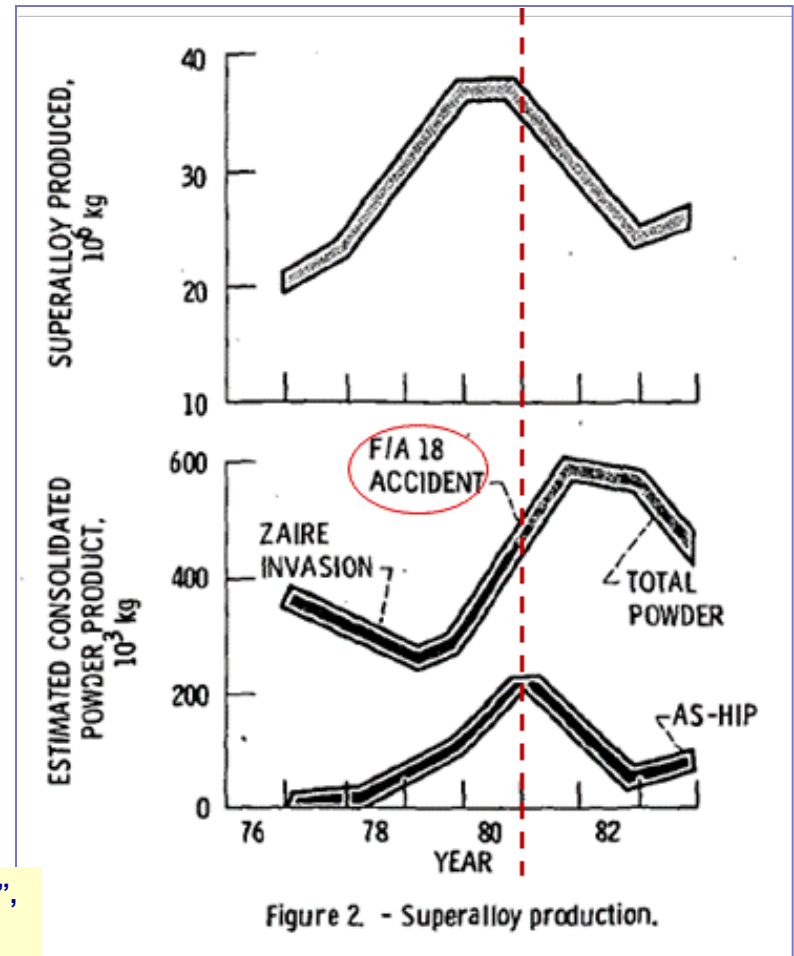


- **An event which strongly influenced the direction of P/M superalloy technology, especially as-HIP, was the loss of an F/A-18 aircraft in September 1980.**
- **The crash was attributed to the failure of a P/M superalloy low pressure turbine disk.**
 - **The cause of the disk failure has not been conclusively established as portions of the failed disk critical to the failure analysis were not recovered.**
- **A plausible explanation for the failure of that turbine disk is that it contained a *large undetected flaw* which propagated due to low cycle fatigue until it became critical and fracture occurred**



Effect on Early PM Production Rates

- Shortly after the F/A 18 crash, the production of as-HIP P/M superalloys decreased dramatically.



Reference: "P/M Superalloys – A Troubled Adolescent?", R. L. Dreshfield and H. R. Gray, NASA Technical Memorandum 83623, 1984.

Inherent Anomalies *Specific to PM Alloys*

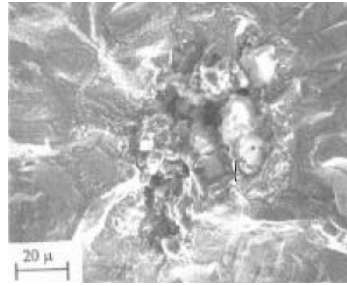
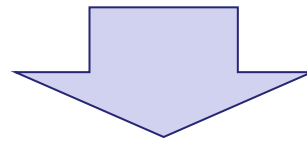
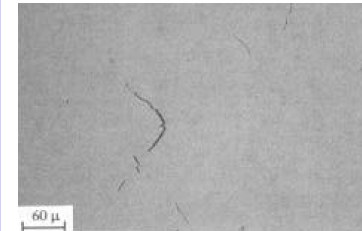


Table I. Major Types of Defects in HIP Rene' 95

Type	Description	Typical Elements	Size, Mils ² (*)	
			Avg.	Max.
1	Discrete chunky ceramic	Al, Mg, Zr, Ca, O	8	50
2	Ceramic agglomerates	Al, Si, Mg, Ca, O	10	110
3	Reactive agglomerates forming PPB	Al, Zr, Cr, Ca, O C, Ca, Fe	15	250
4	Voids	Ar	<2	--



Inherent Anomalies in AM Alloys...

- Lack of fusion..?
- Micro-cracking due to residual stresses..?
- Porosity..?
- Other..? (“known unknowns”)

...Need to be Understood, Characterized and Managed



Lessons Learned Summary

- Early failures in high-criticality applications have a **major impact on new technology**
- **Scale-up challenges** – transitioning from well-controlled development environment to full-scale production
- **Good understanding of the key failure modes and material anomalies is crucial**
 - And **needs to be connected to manufacturing process controls and NDI methods**
- **Initially believed to be an innocuous material system change, subject to conventional design criteria...**
 - ... Ended up giving rise to a **new probabilistic lifing framework** used for both military and commercial certification
 - Highlights importance of **managing uncertainty and variation**



What Did Historically Work Well to Address “Known Unknowns”?

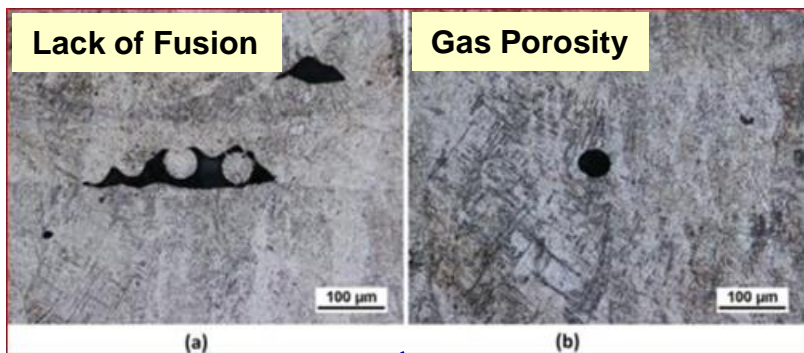
- Effective manufacturing process controls
- *Damage tolerance (DT) framework*
- QA / NDI methods
- Sharing of lessons learned across the industry

Success story – rotor-grade Titanium alloys

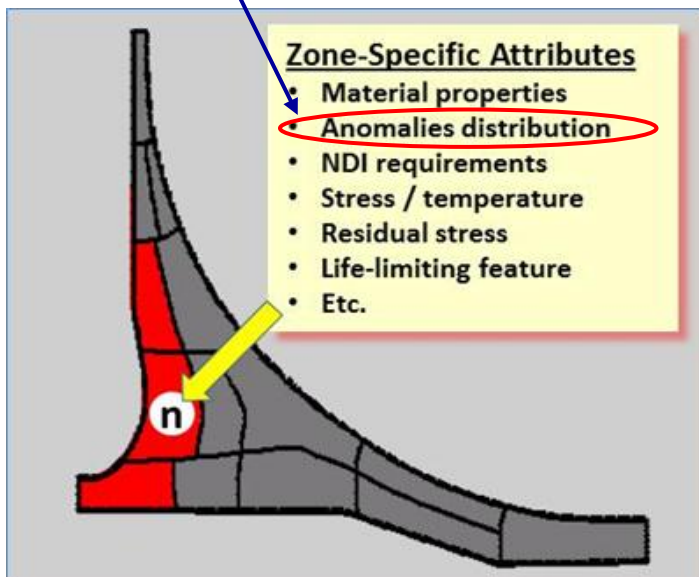
(Reference: proceedings of AIA RISC Working Group)



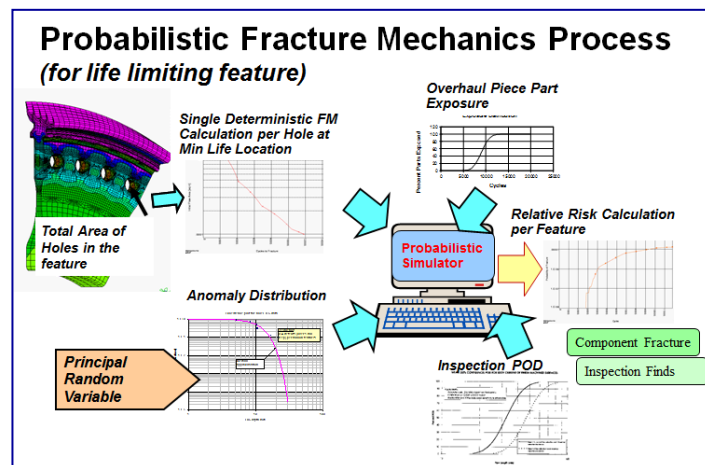
Part Zoning Considerations



- AM parts are uniquely suited for *zone-based evaluation*
- Concept is similar to zoning considerations for castings...
- ... however, modeling represents a viable alternative to empirical “casting factors”



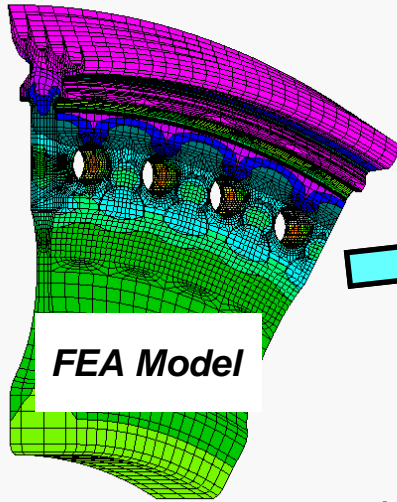
One Assessment Option – PFM *)



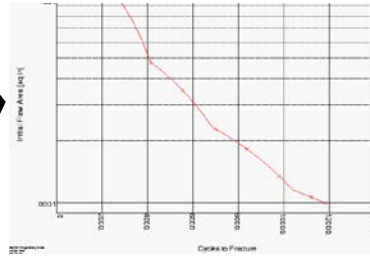
*) PFM - Probabilistic Fracture Mechanics
(see next page)



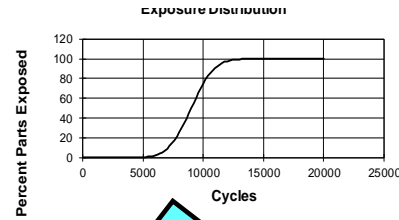
Example: PFM Process (for a life limiting feature)



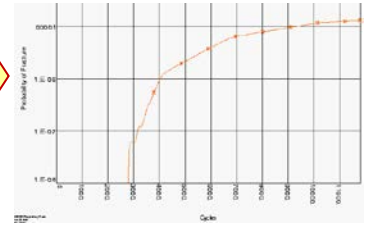
Single Deterministic FM Calculation per feature at Min Life Location



Overhaul Piece Part Exposure

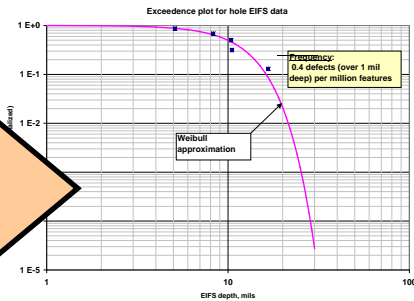


Relative Risk Calculation per Feature



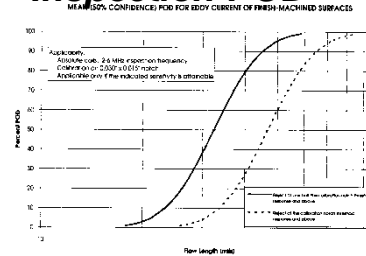
Probabilistic Simulator

Anomaly Distribution



Principal Random Variable

Inspection POD



Component Fracture

Inspection Finds



Summary

- Expected (rapid) expansion of AM in Aviation, and increase in the levels of AM parts criticality
- *Development of industry standards and specs are key enablers*
- Most OEMs and agencies support *risk-based approach*, including *“system-level” considerations*, including:
 - Manufacturing process controls, specs development
 - Characterization of key failure modes and anomalies
 - Lifting system and certification criteria
 - QA, Process Monitoring and NDI methods
- Need to leverage historical “lessons learned” and risk mitigation strategies ... *including appropriate use of DT principles for more critical applications*



Discussion



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