National Aeronautics and Space Administration

# Methodology for Substantiation of Design Values in Additive Manufacturing

## *Importance of Equivalence Methods*

CMH-17 Additive Manufacturing Coordination Committee
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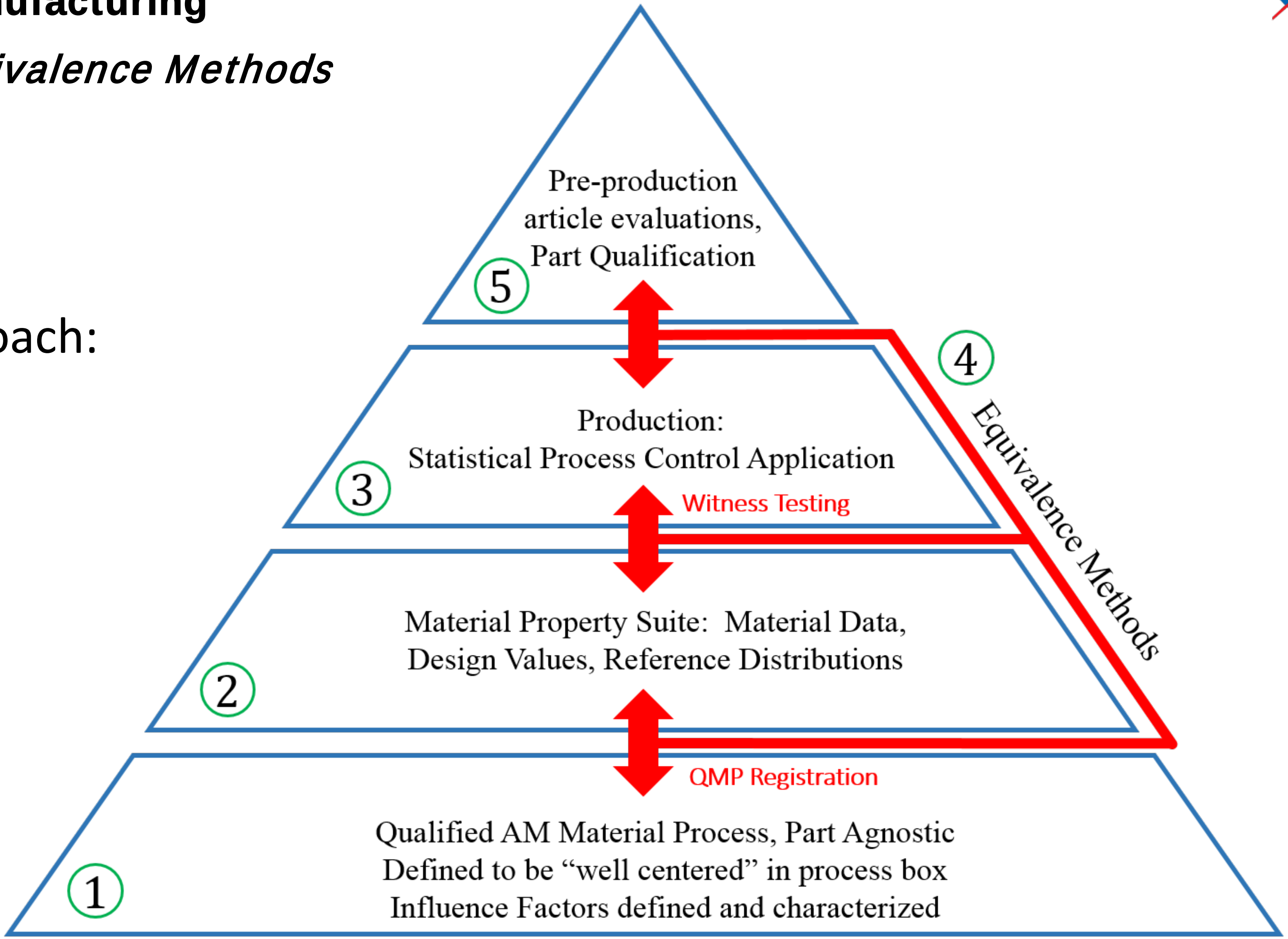
*Importance of Equivalence Methods*

A “Building Block” Approach:



# Methodology for Substantiation of Design Values in Additive Manufacturing

*Importance of Equivalence Methods*

**STEP 1: AM Process Qualification (part agnostic, with some exceptions)**

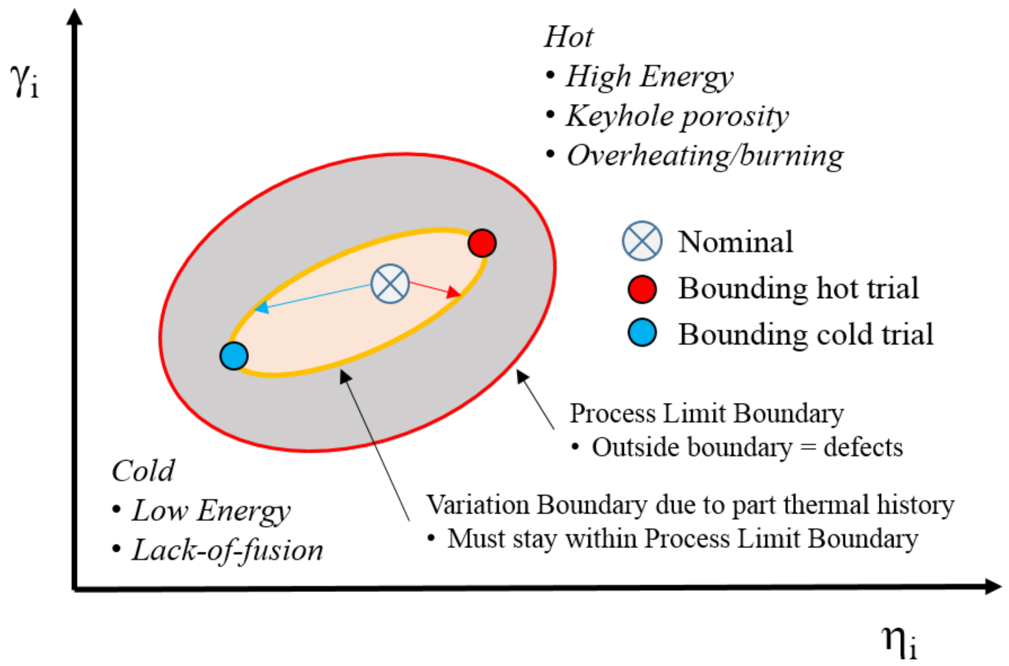
A. Define a baseline, locked AM candidate process by machine serial number
   - Candidate process refined to produce high material and build quality under nominal conditions
   - Candidate process "well-centered" in the AM process box
   - Candidate process definition includes all "key parameters" influential to material performance
     - Feedstock, AM machine conditions/settings, post-build thermal treatments

B. Qualify the candidate process using commonly accepted metrics (no standards yet) to an accepted and understood state of inherent, yet acceptable "discontinuities" (defect state)

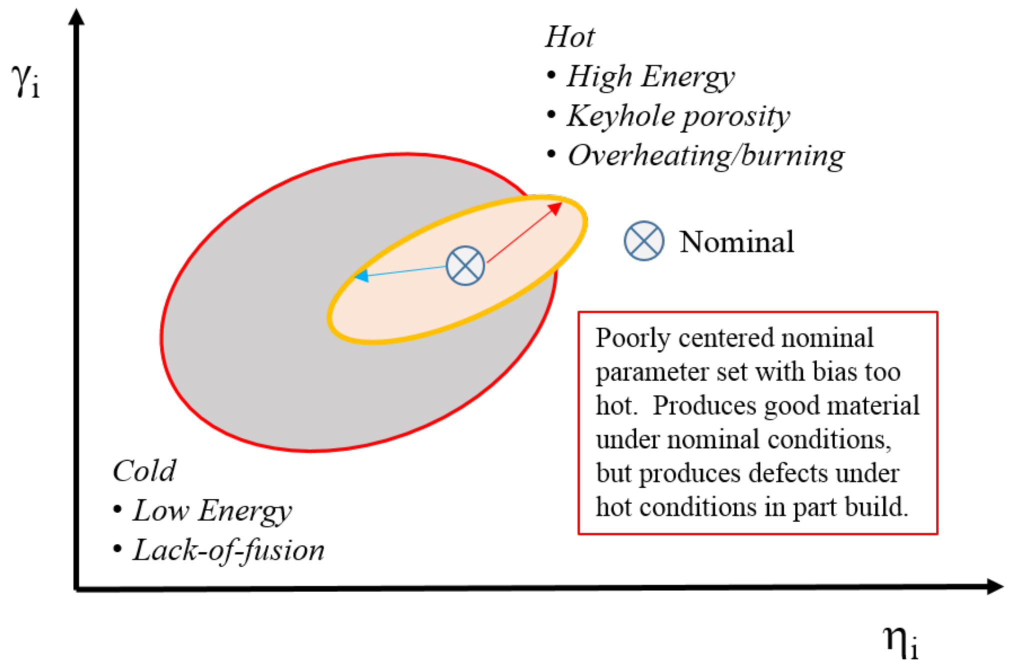
C. Characterize material performance of qualified baseline process as required for Q&C

D. Identify AM-specific "influence factors" that may alter material performance.
   - (Thermal history, thin sections, surface finish, orientation, etc.)
   - Characterize the effects of influence factors in a bounding, containable fashion based on understanding of process physics
   - Define standard methods of application of "influence factors" to baseline data

# Well-Centered AM Process:
# Example from Metallic Laser Powder Bed Fusion




(a) Well-Centered Process




(b) Poorly-Centered Process

## Design Data for Q&C

**STEP 2: Establish common design value properties based upon baseline process and influence factors**

- Maintain both design values and supporting data characteristics used in their development
- Nominal material performance definitions eventually become part of industry handbooks

**STEP 3: Establish statistical process controls that maintain material quality and performance standards throughout production**

- SPC metrics are likely the required on a variety of factors to achieve control to defend design values

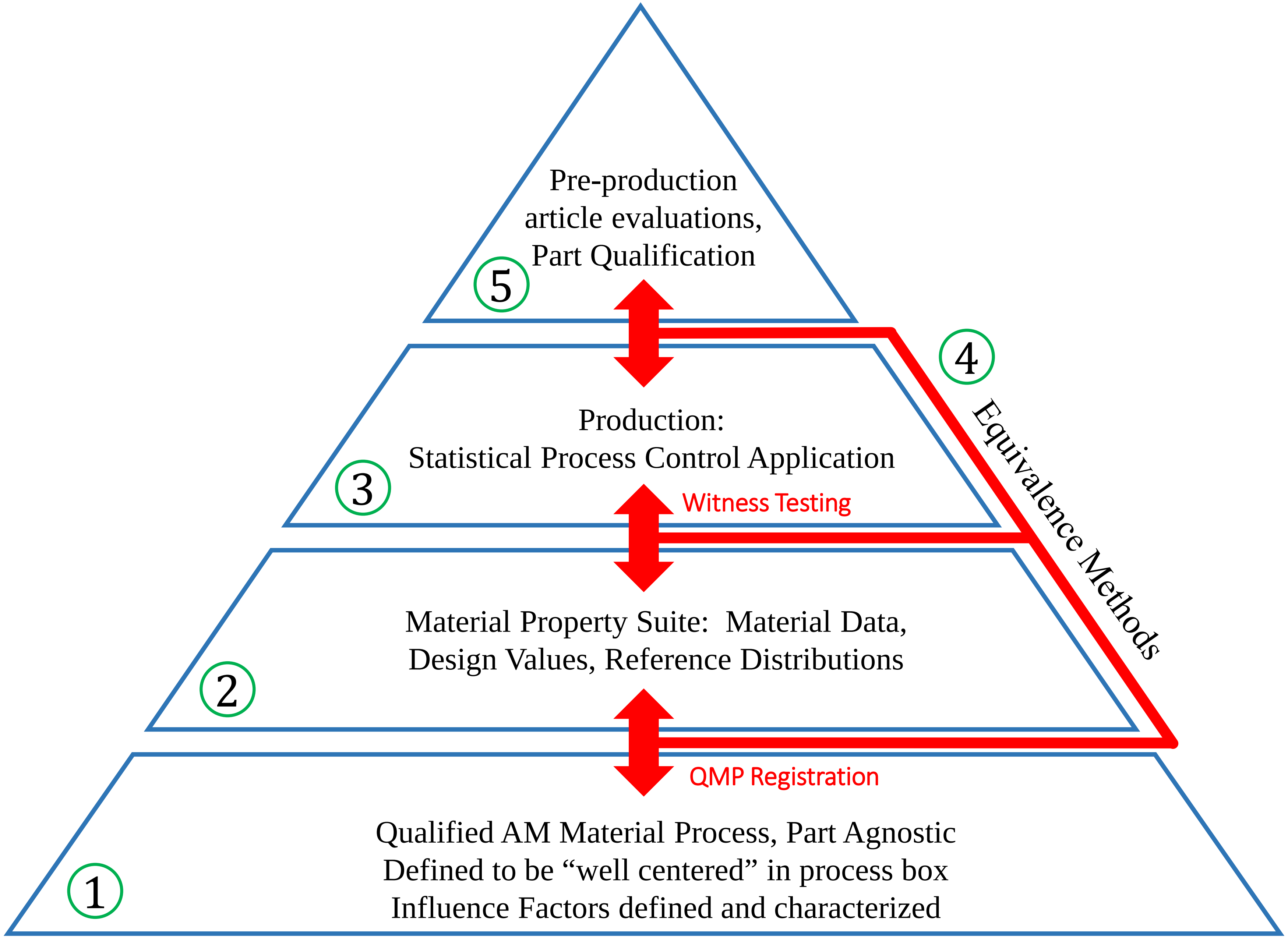
**STEP 4: Demonstrate AM Material Performance Equivalence**

- Use statistical equivalence methods to demonstrate additional qualified processes (machines) may justifiably use the established common material properties (with prerequisites).
- Nominal equivalence methods eventually become part of industry handbooks, enabling use of handbook design values
- Equivalence does not mean equal or better, but equivalent in fundamental material aspects including feedstock/chemistry controls, microstructure, properties and performance on multiple metrics

**STEP 5: Maintain a strong Part Qualification process that ensures each implementation of the qualified AM process and application of properties (and influence factors) has been successful relative to the assumed material performance standards.**

# MSFC Equivalency

Cordner


Pre-production
article evaluations,
Part Qualification
5
4
Equivalence Methods
Production:
Statistical Process Control Application
3
Witness Testing
Material Property Suite: Material Data,
Design Values, Reference Distributions
2
QMP Registration
Qualified AM Material Process, Part Agnostic
Defined to be "well centered" in process box
Influence Factors defined and characterized
1

# Data Requirements for QMP Registration

TABLE II. Minimum mechanical property evaluation requirements for qualification of candidate metallurgical processes as a Master QMP.

| Item | Property | ASTM Standard* | Quantity | Notes |
|---|---|---|---|---|
| 1 | Tensile | E8/E8M | 15 | Survey of build area and materials from "hot" and "cold" processes variants per Section 4.2.3.1 (b) |
| 2 | Tensile, With process restart | E8/E8M | 5 | Required if process restart is allowed. Tensile testing of process restart interface. Item 2 tests not required if restart is included in testing for Item 1 |
| 3 | High Cycle Fatigue | E466 | 10 | Five (5) tests to MPS PCRD fatigue condition, and five (5) tests at cyclic stress range producing failure $> 10^6$ cycles that replicate R-ratio and stress range of existing MPS data enabling comparison |
| 4 | Low Cycle Fatigue | E606/E606E | 5 | Five (5) tests at a cyclic strain range represented in MPS data |
| 5 | Fatigue, With process restart | E466, E606/E606E | 5 | Required if process restart is allowed. Fatigue testing of process restart with HCF or LCF, five (5) tests at the MPS PCRD fatigue condition. Item 5 tests not required if restart is included in tests from Item 3 and/or 4. |
| 6 | Fracture Toughness | E1820, E399 | 3 | Tests with crack parallel to build plane, loading in Z direction. |
| 7 | Tensile (at Temperature) | E21, E1450 | 6 | Three (3) tests per temperature at two or more temperatures – either the high and low bounding temperatures of the MPS or other applicable temperatures. |
| 8 | Customized QMP | As specified | 2 | Test at conditions defined by the candidate metallurgical process required for acceptance, minimum two (2) tests at condition. |

*Other test standards approved by the CEO may be used.

# Data Requirements for Witness Testing

**TABLE III. Witness specimen quantities for stand-alone acceptance**

| | Class | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **A1** | **A2** | **A3** | **A4** | **B1** | **B2** | **B3** | **B4** |
| Tensile | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| FH Contingency | 1 | 1 | 1 | 1 | 1 | 1 | - | - |
| Metallography | 2 | 2 | 1 | 1 | 1 | 1 | - | - |
| Chemistry | 1 | 1 | - | - | - | - | - | - |
| HCF | 2 | 2 | 2 | 2 | 2 | - | - | - |
| Low Margin Point | A/R | A/R | - | - | - | - | - | - |
| Witness sub-article | A/R | - | A/R | - | A/R | - | - | - |
| Witness article | 1 for 6 | - | - | - | - | - | - | - |
| CQMP | A/R | A/R | A/R | A/R | A/R | A/R | - | - |

Notes:

FH Contingency = Full-height contingency specimen

A/R = As required when specified in the PPP/QPP

# Origin of this Equivalence approach

- Other methods focus on one property at one point in time for large sample sizes

- Not a statistician
- Came up with this method to solve a MSFC issue
- Coincidentally roughly follows the approaches outlined in CMH-17
- Ongoing research (many OEM's and SDO's)

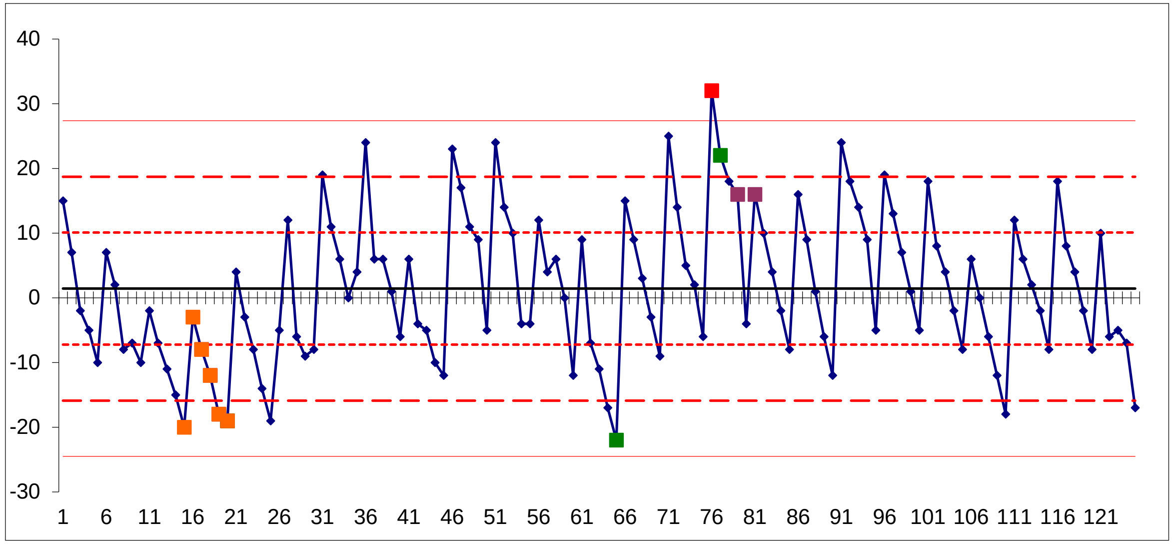
# Break down of equivalence

- Gains robustness from testing several different properties as well as metallography

- Control Charts
- Multivariate Plots
- Single Point Statistical Check

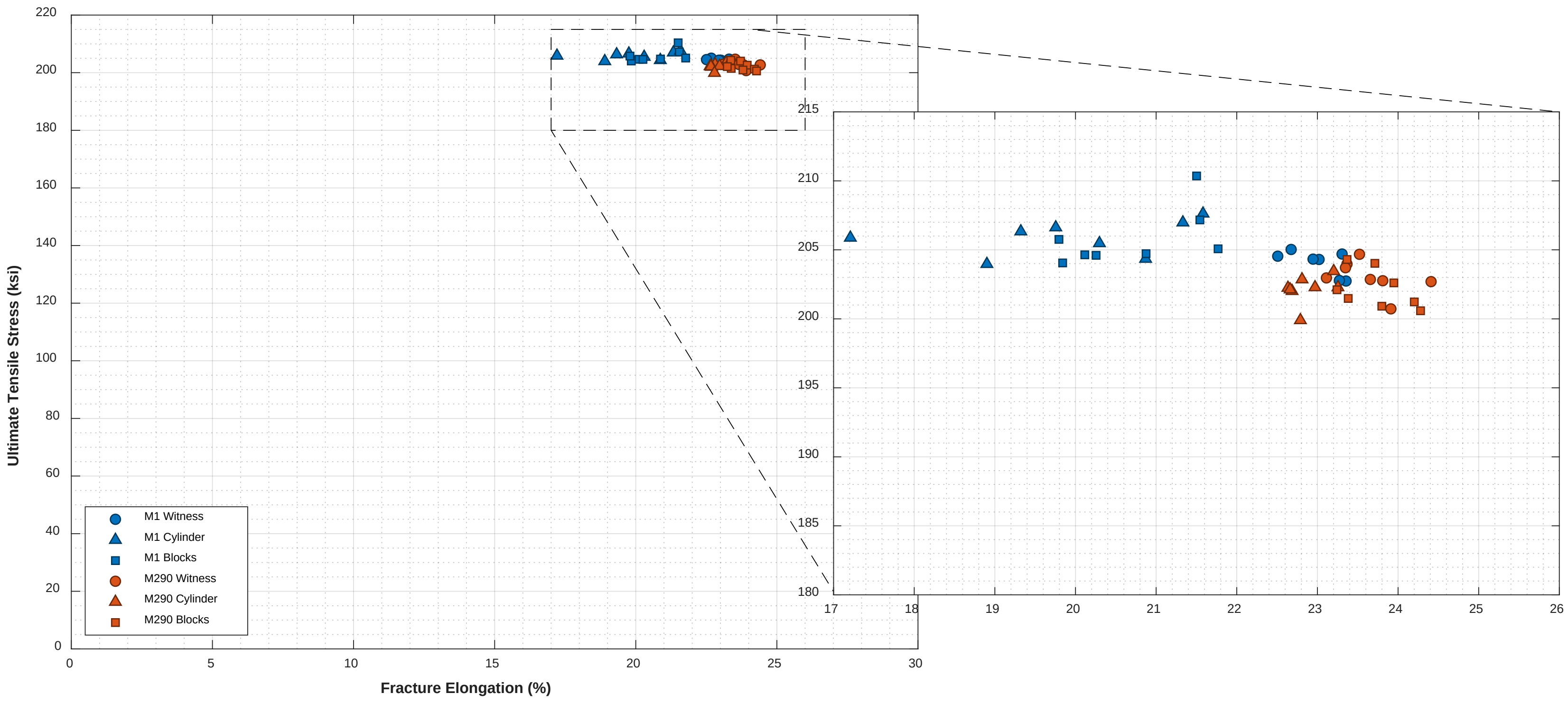
# Control Charts

- Since build to build variability is the largest source of variability, Control Charts are probably the best way to monitor for changes in process. If this is used well, you could possibly lower the witness sample number.
- The down side is that you must wait 5-10 builds.



# Multivariate Plots

- Great for getting an engineering sense if the data is coming from the same process
- Plot 2 different results on different axis



# MSFC Statistical Check

- Test on Minimum value
  - Comparison to the T99
- Test on Mean Value
  - Comparison to the T90
- Test on Standard Deviation
  - Comparison to typical standard deviation
    - Does some checking of outliers
- Metallography

- Not everything is perfect here with fatigue and elongation.

# Future Work

- Most AM data is structured and the idea that the data comes from a known distribution may be false.
- Work with others to derive the most practical robust solution for small sample equivalence.
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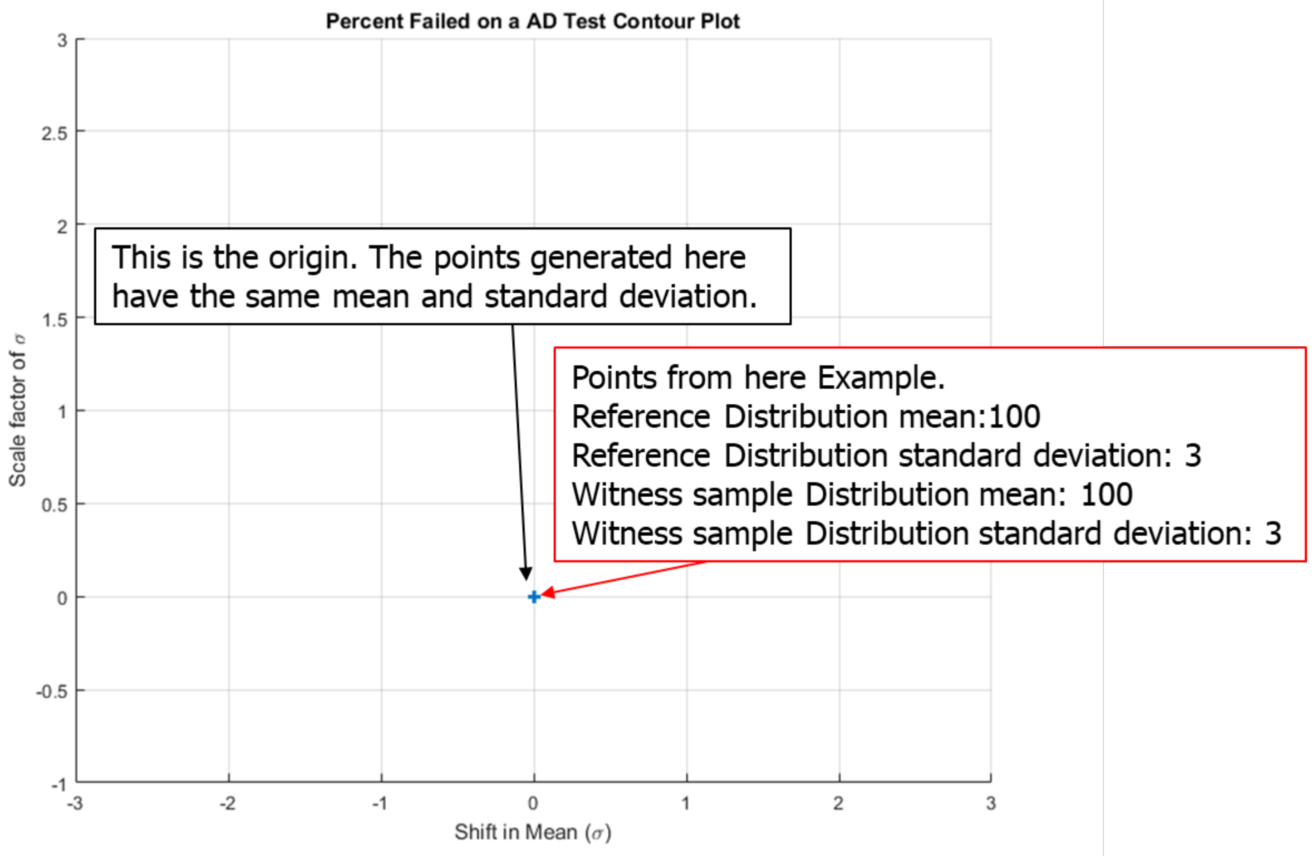
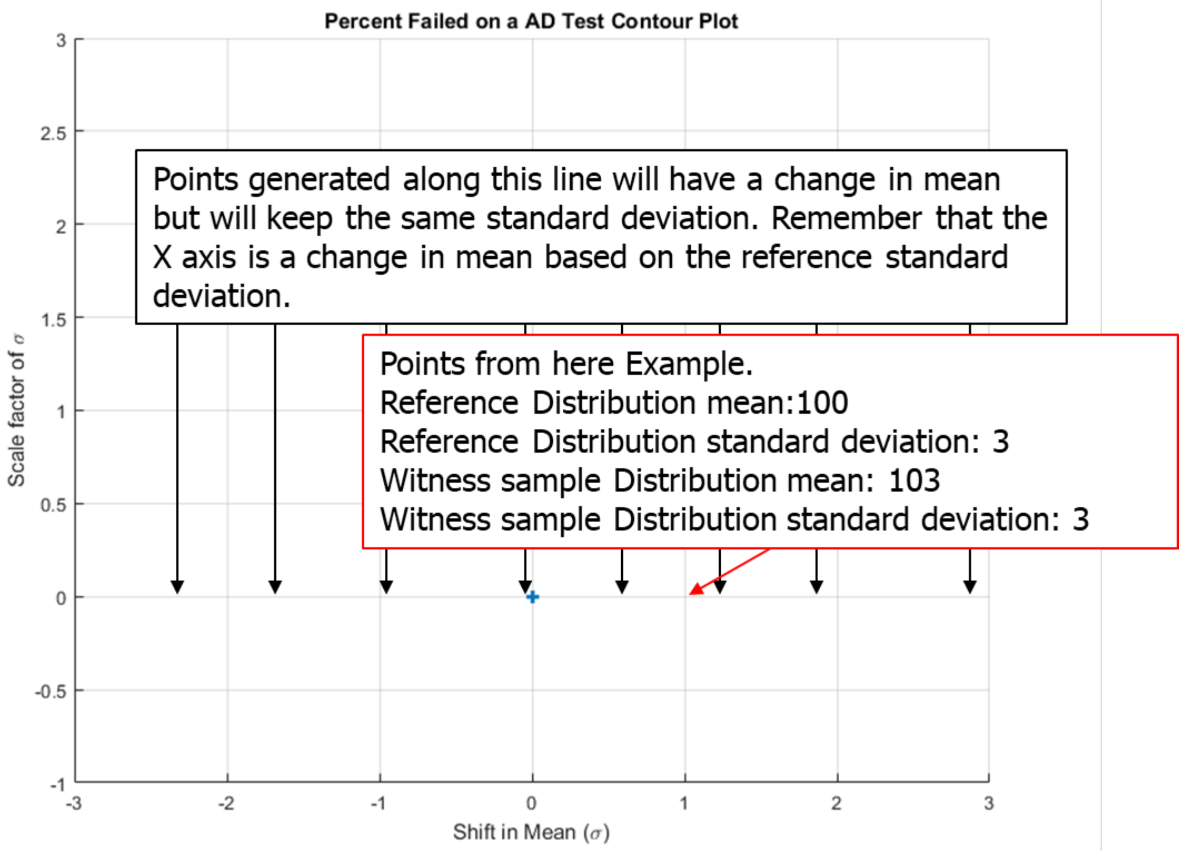
# Intro of Monte Carlo Simulation Chart

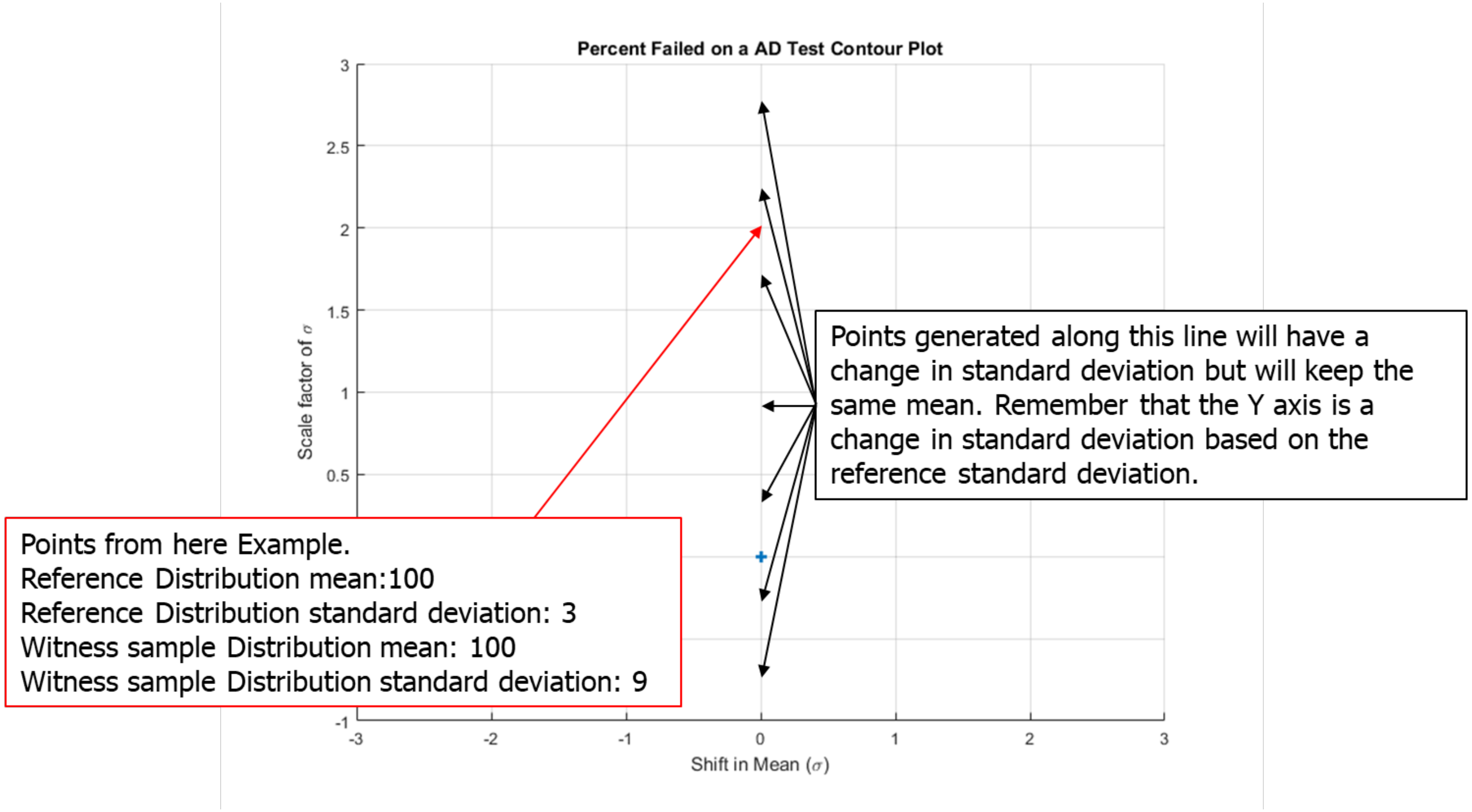
# Graph Explanation – Single Point



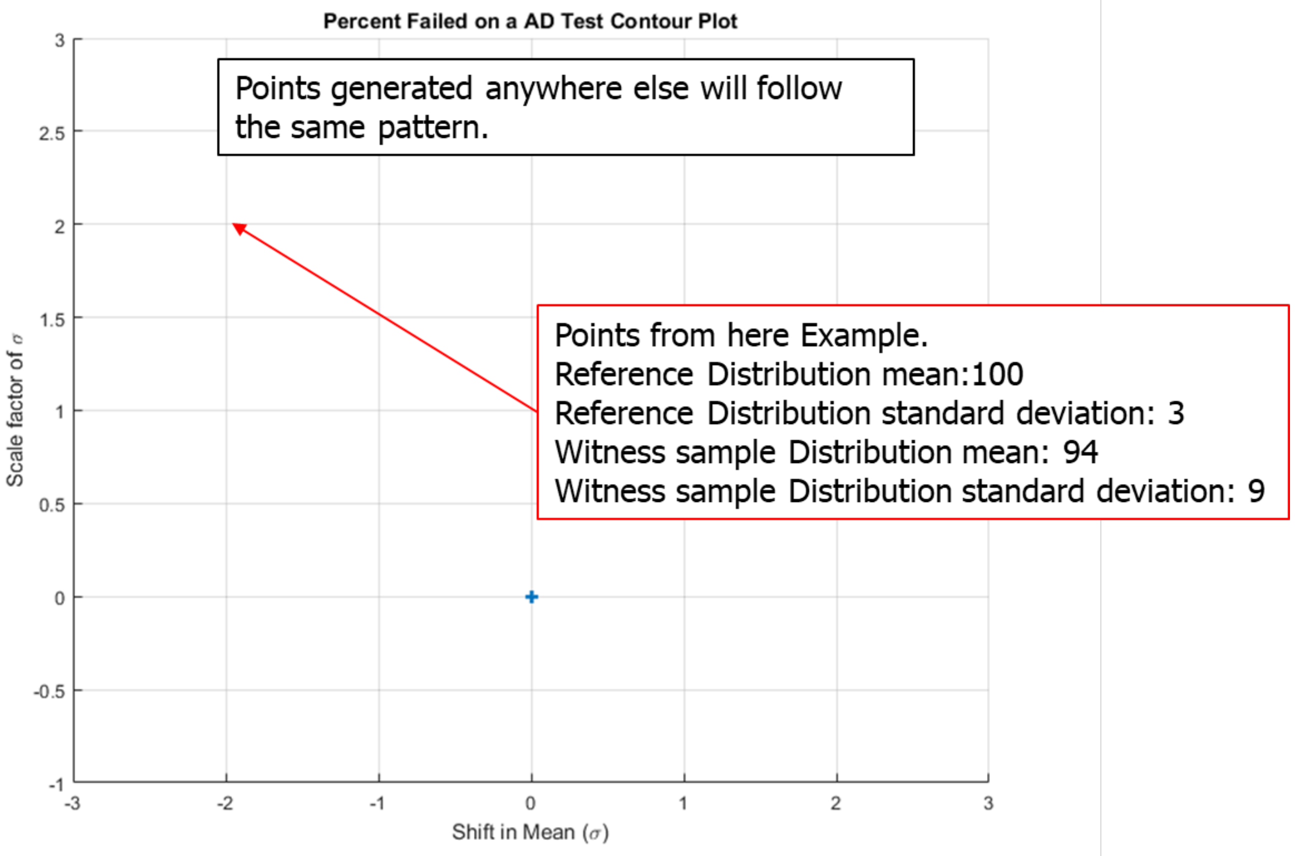
# Graph Explanation – Variation in Mean



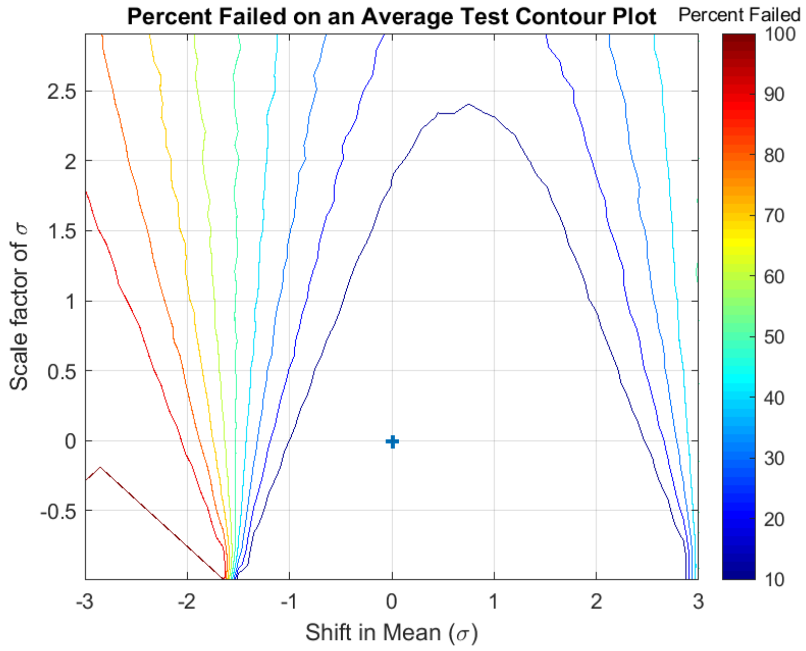
# Graph Explanation – Variation in Standard Deviation



# Graph Explanation – General Variation

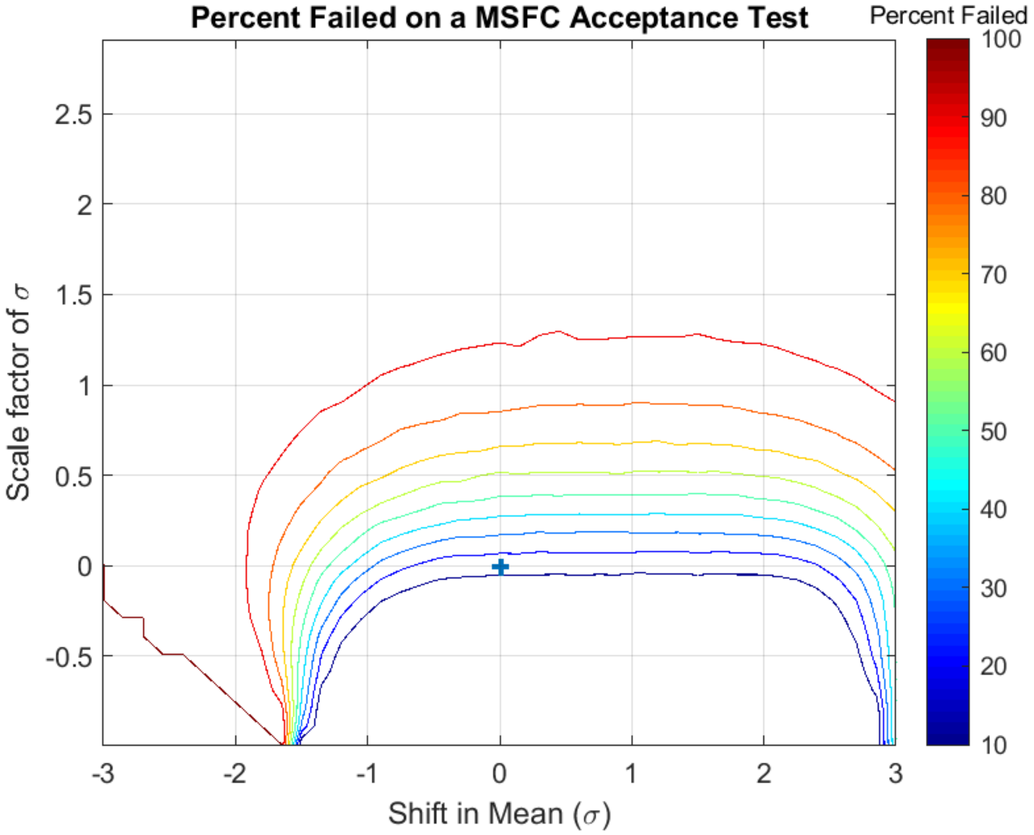


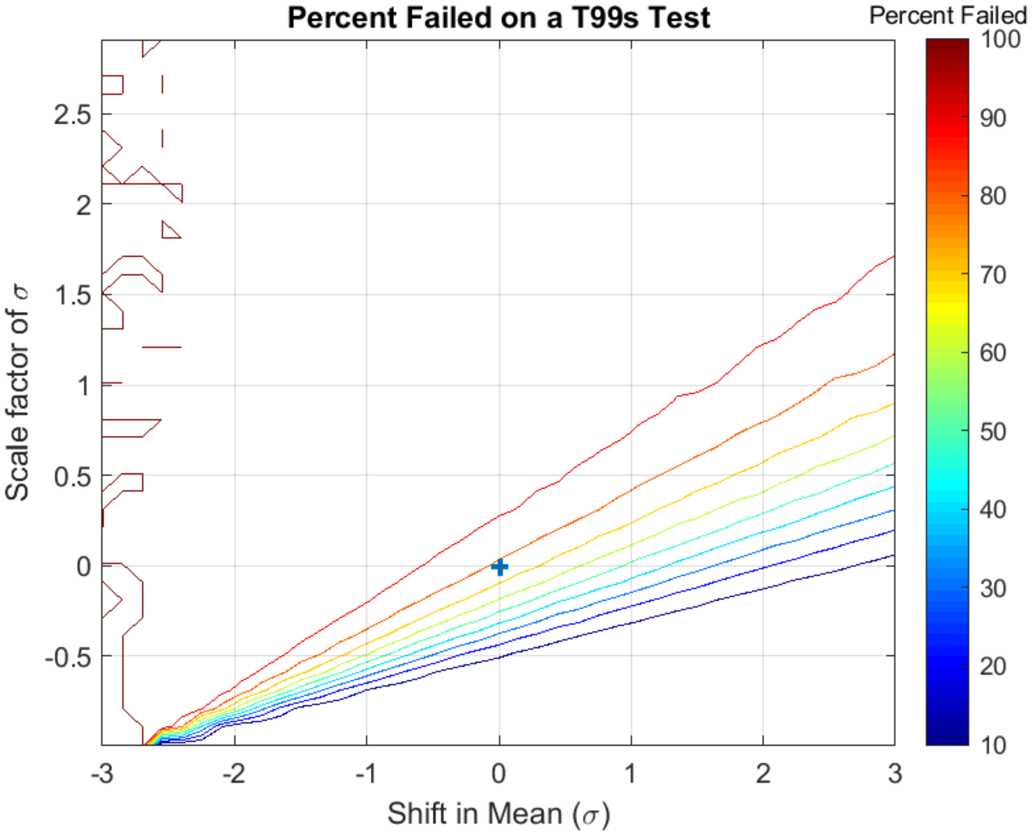
# Graph Explanation – Contour Color Axis



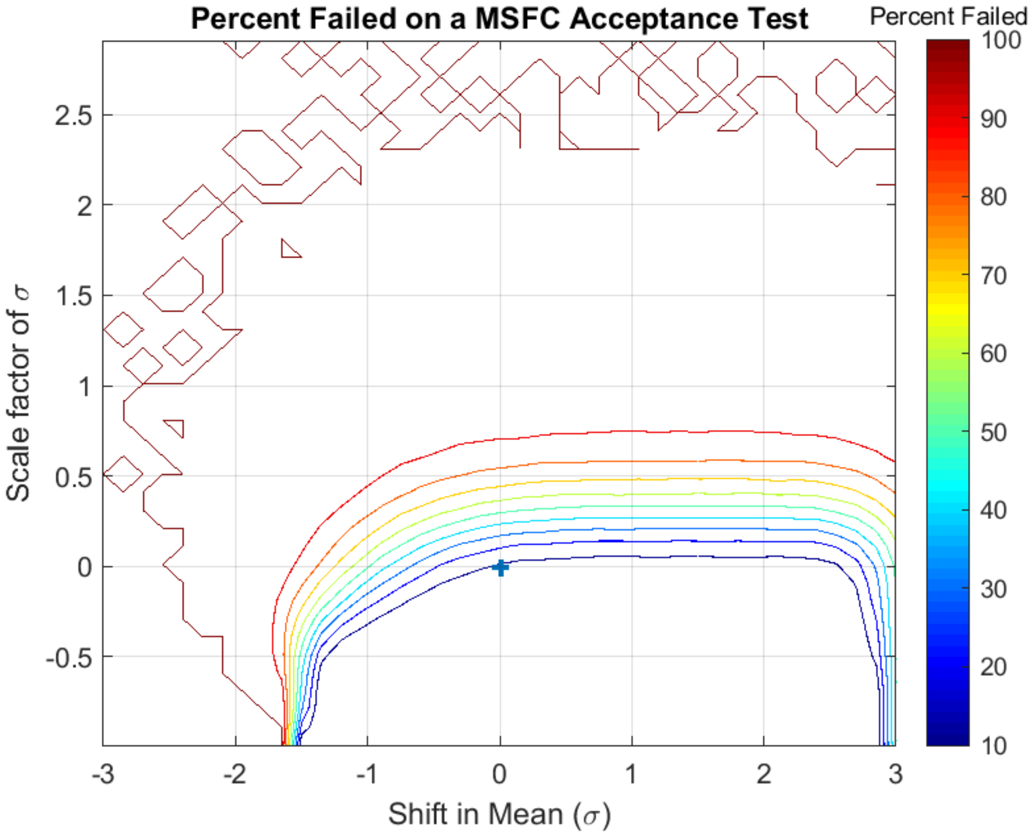

- To reiterate, each point represents a sample that comes from different distribution.
- Since the samples are drawn at random from their respective distributions, the actual sample may not have the mean and standard deviation as their point suggests. This is done intentional as to help identify how the random nature of sampling should affect the tests.
- Because of this random nature, each point is ran thousands of times.
- At each point, the further red the point is, the greater odds that the test will fail at that sampling point.
- This graph can also be shown as a contour plot so that graph details are evident.

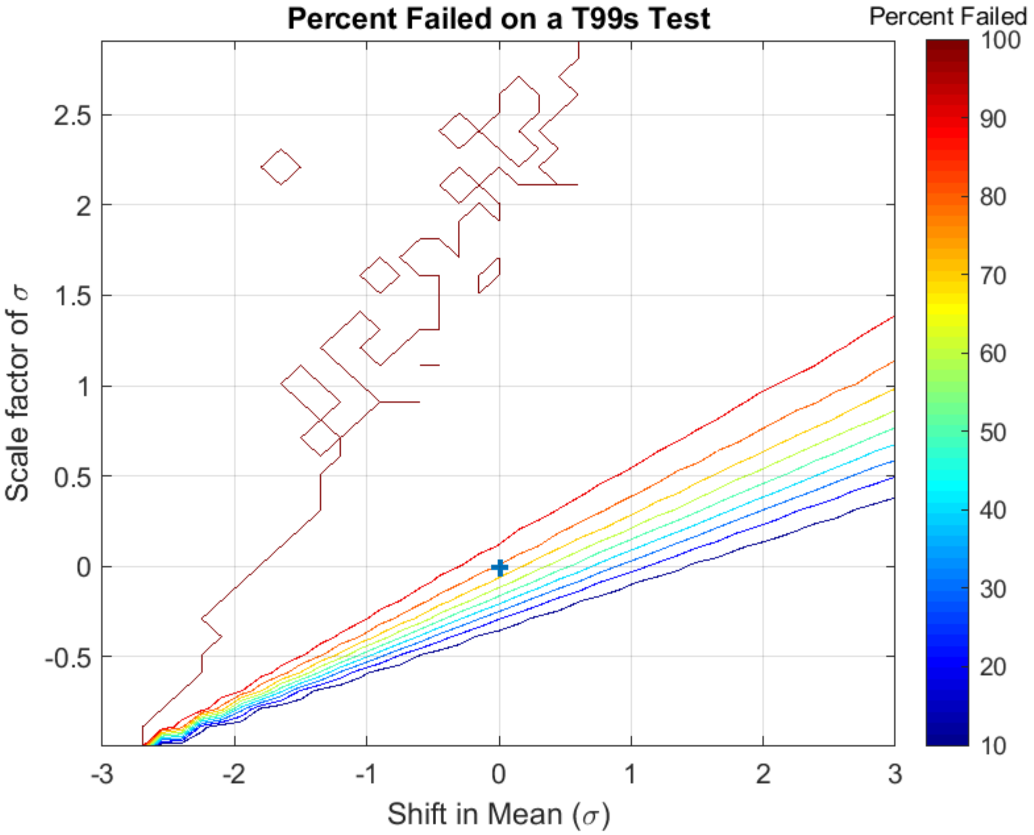
# Sample Size of 6



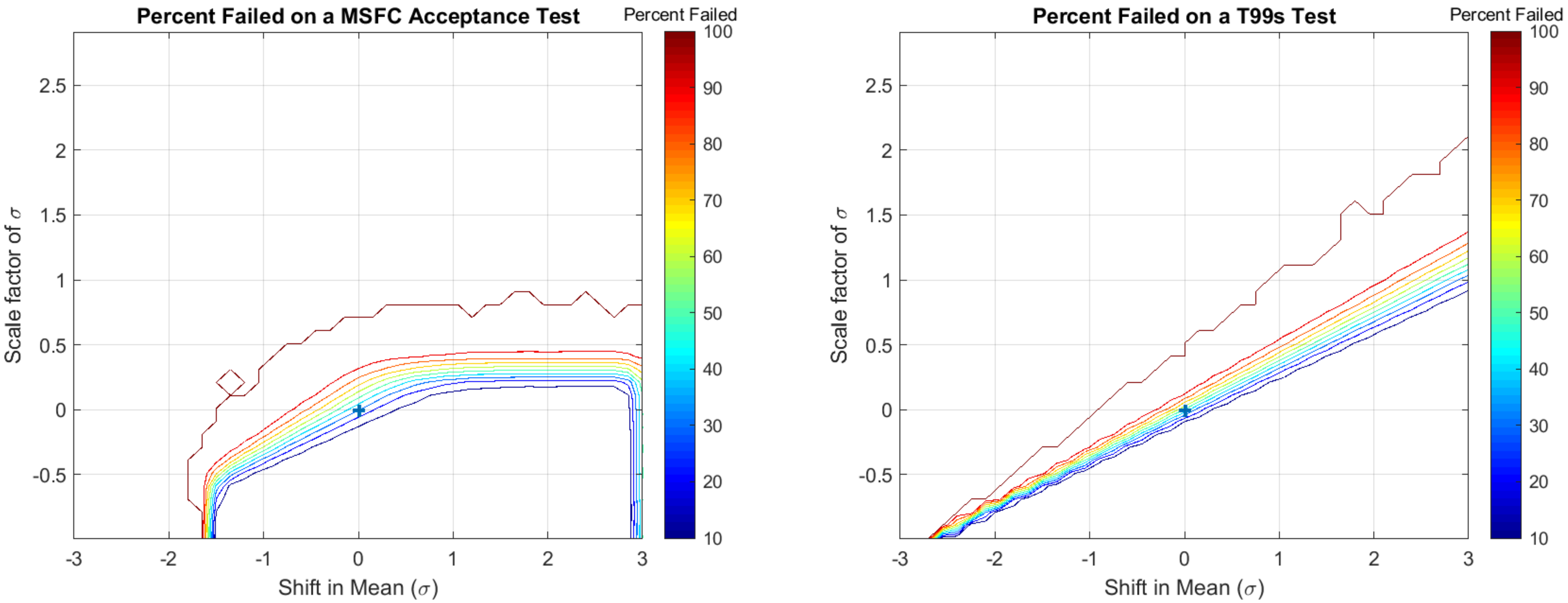



# Sample Size of 15



# Sample Size of 100



# Conclusions

- Equivalence is used at several stages of the AM process
- Equivalence is more than greater than one property
- More discussions need to be had about small sample sizes