Production Control Effect on Composite Material Quality and Stability

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A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

WICHITA STATE UNIVERSITY

CECAM center of excellence for composites and advanced materials

The Joint Advanced Materials and Structures Center of Excellence

Production Control Effect on Composite Material Quality and Stability

- Motivation and Key Issues
  - Quality control tests on prepreg or lamina (i.e. receiving inspection or acceptance tests) may not always detect material defects
  - Material suppliers (e.g. fiber, resin, prepregger, etc.) and part fabricators need to have an understanding of each others' roles and responsibilities
- Objective
  - Develop essential information on the nature of the controls required at various producer levels to assure the continuation of stable and reliable composite raw material for aerospace usage
    - Develop and clarify requirements
  - Provide guidance to NASA's National Center for Advanced Materials Performance
- Approach
  - Develop production control guidelines
  - Use NCAMP as the proofing ground
  - Document what works and what doesn't
  - Define "aerospace grade"

FAA Sponsored Project Information

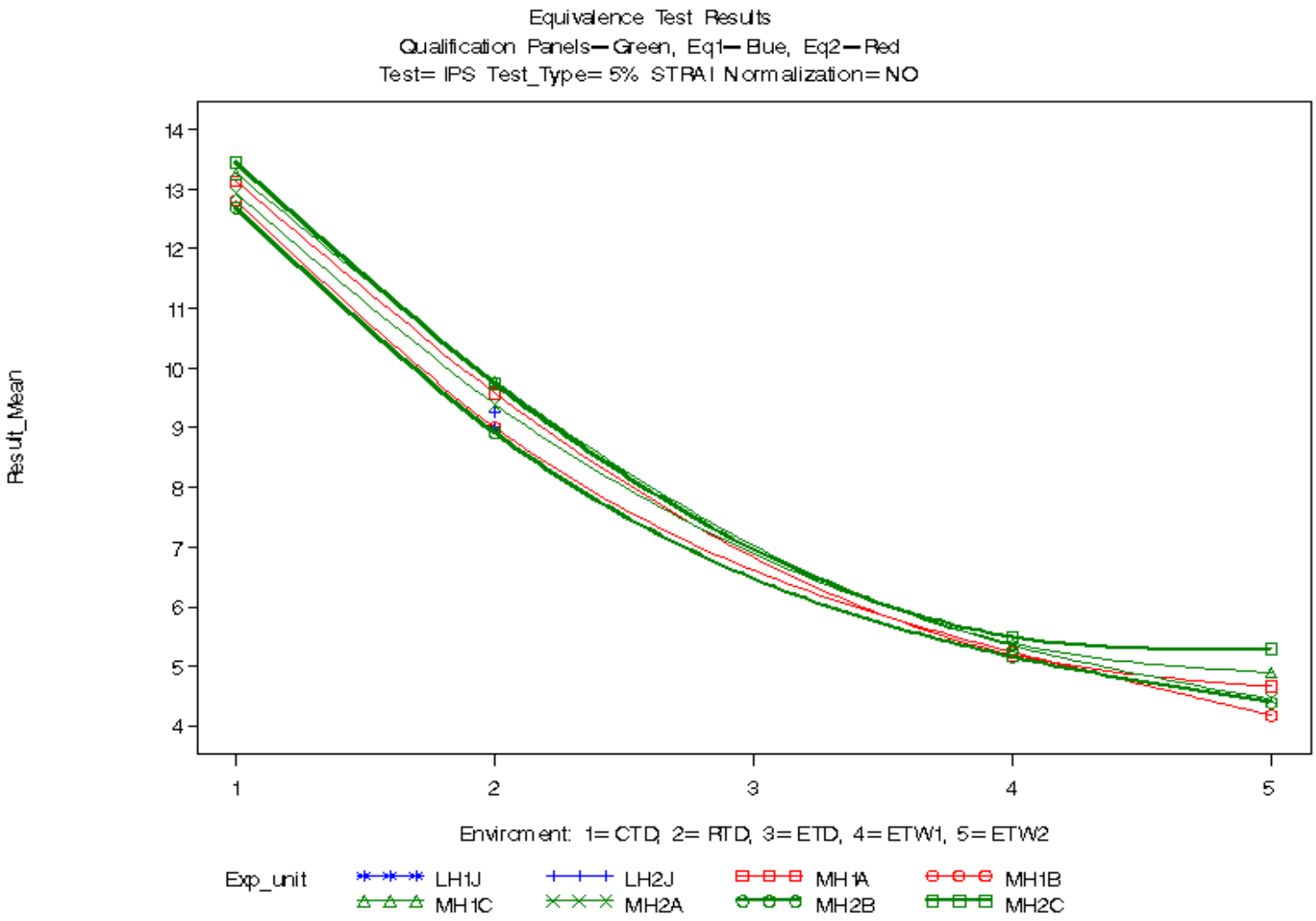
- Principal Investigators & Researchers
  - John Tomblin, Yeow Ng, Beth Clarkson, Allison Crockett
- FAA Technical Monitor
  - Curtis Davies
- Other FAA Personnel Involved
  - Larry Illcewicz, Peter Shyprykevich (retired), Lester Cheng, Evangelina Kostopoulos, and David Ostrodka (retired)
- Industry Participation
  - 20 Aircraft Companies and Tier-1 Suppliers
  - 16 Material Suppliers
- Other Partners
  - CMH-17 (formerly MIL-17), SAE P-17, SAE PRI Nadcap, SAE PRI QPL, ASTM D30
  - University of British Columbia and Center for Nondestructive Evaluation at Iowa State University

Control Chart Techniques

- CMH-17 was used to interface with industry
  - CMH-17 chapter 8 has been revised to include additional information on control charting techniques including the multivariate control chart discussed here last year.
- By incorporating new research into the composite materials handbook, it can quickly become an industry standard

Multivariate Approach to Equivalence Testing

- Develop an analysis for a complete set of composite material test results that will output a single yes or no response to whether or not two materials are equivalent that aligns with the *practical* significance of the differences.
- Develop a set of classification criteria along with engineering basis values applicable to the each defined class.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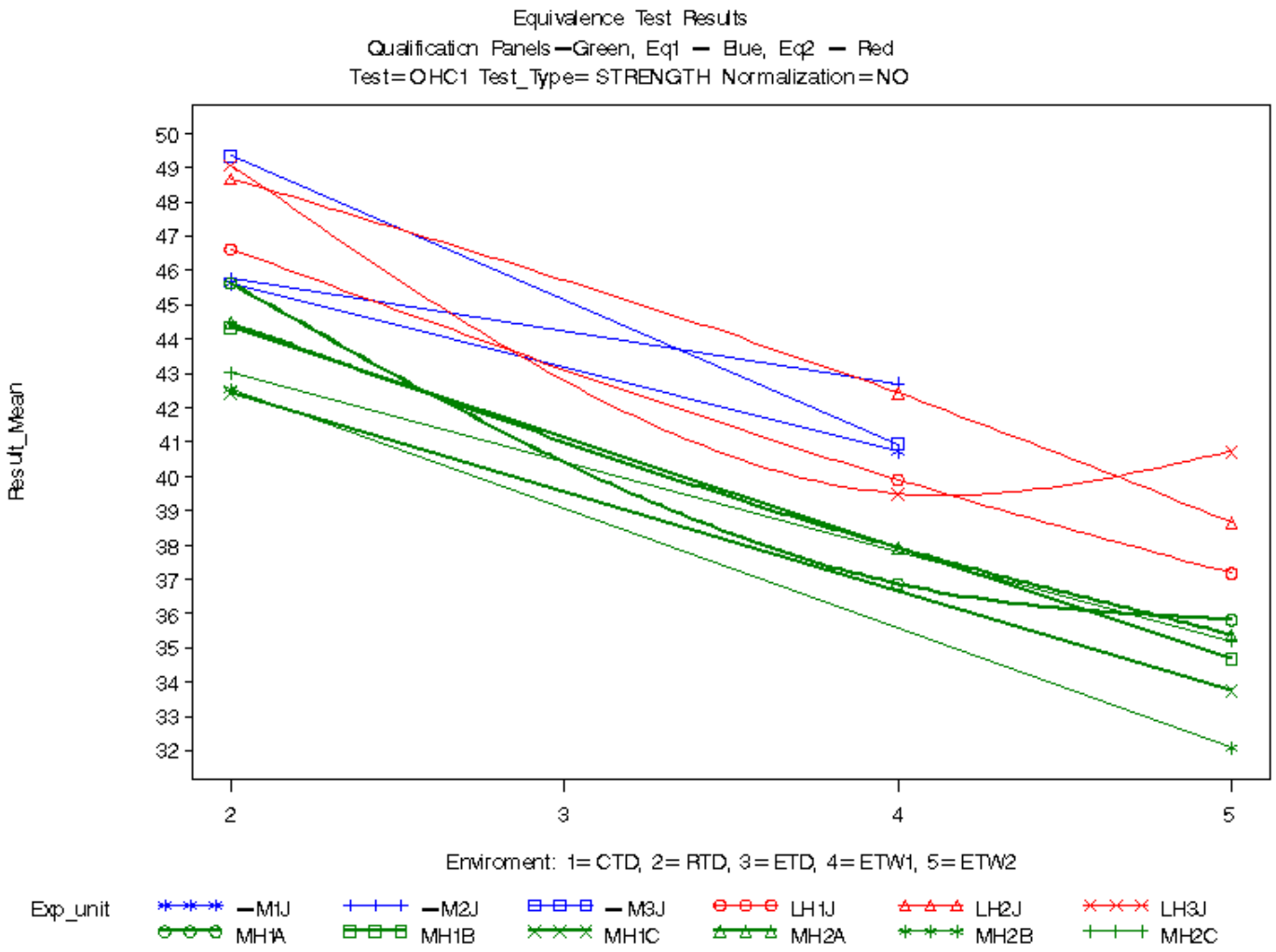
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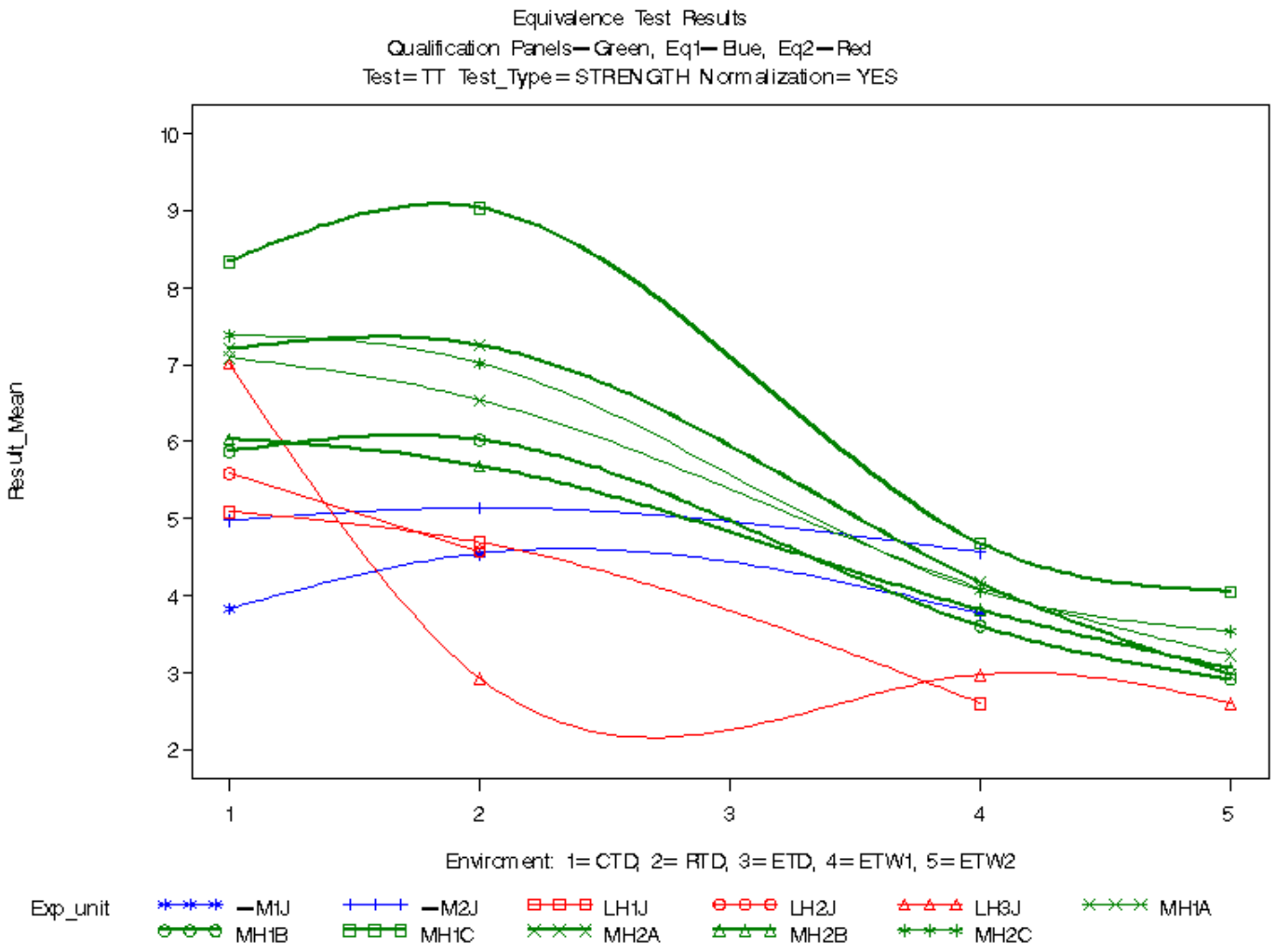
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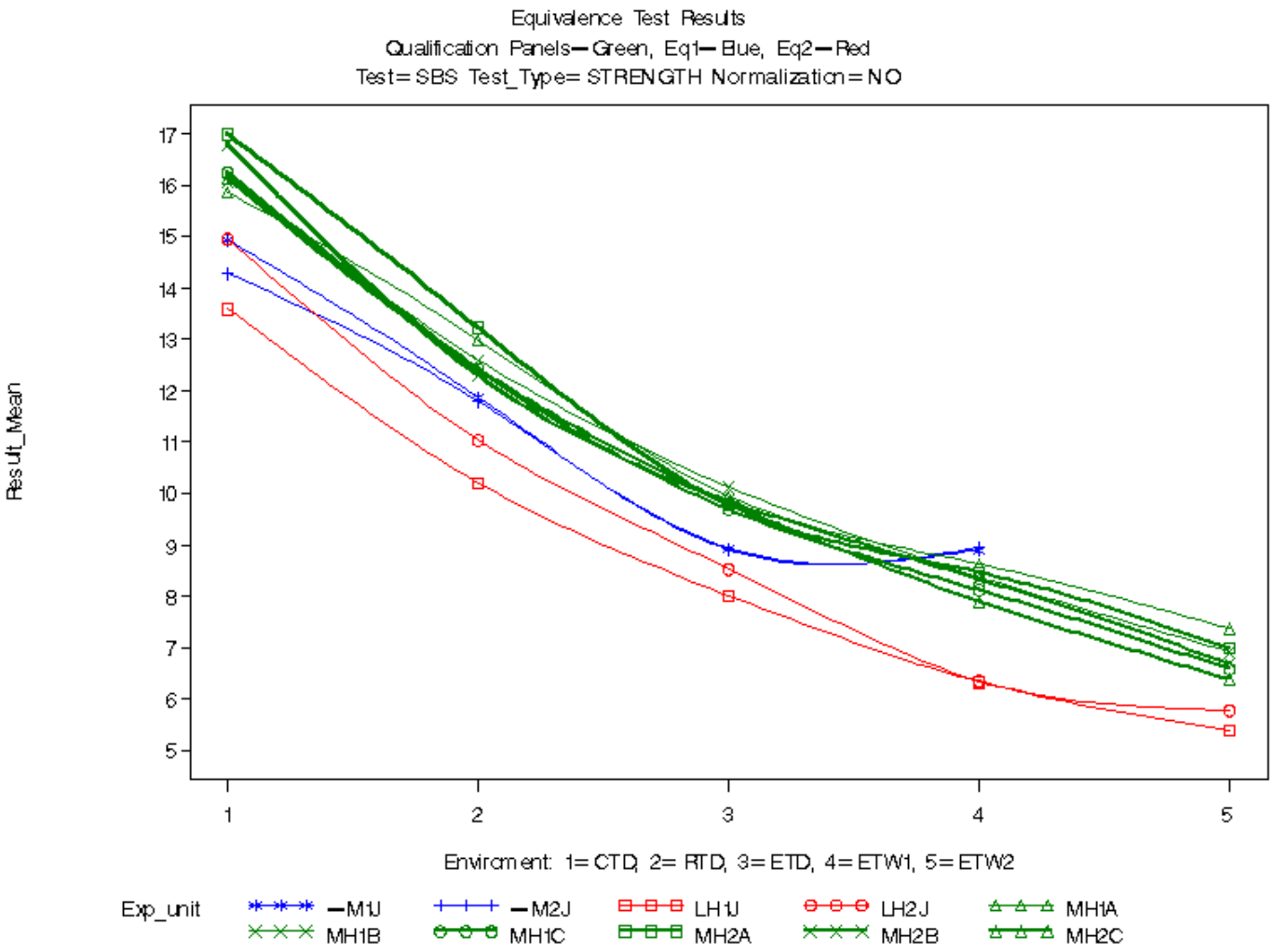
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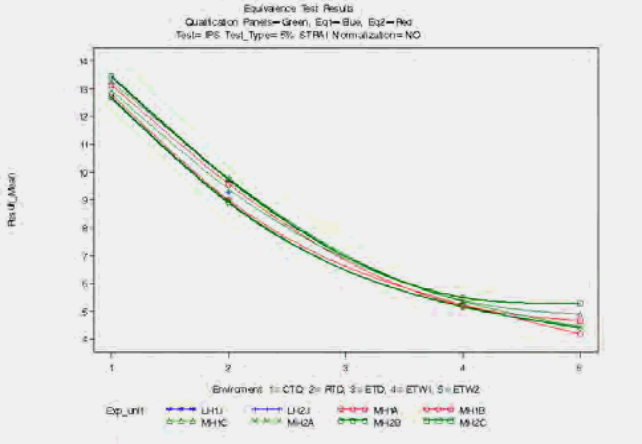
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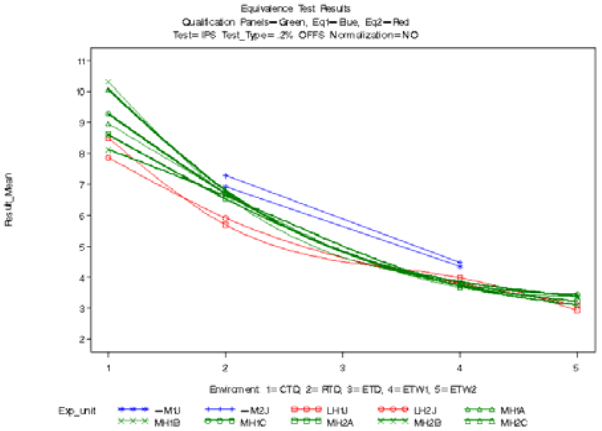
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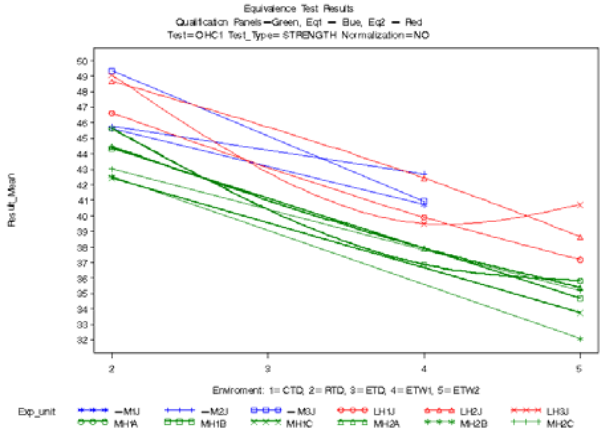
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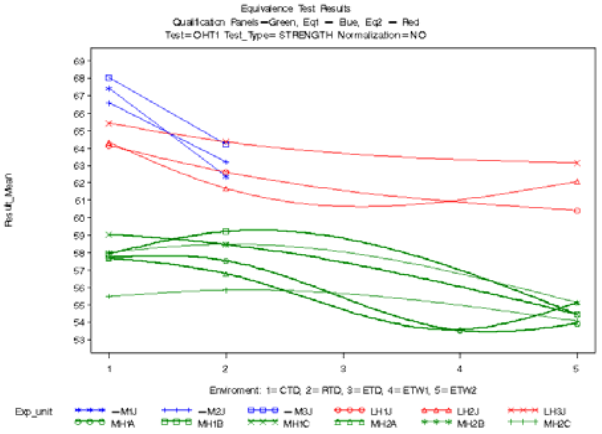
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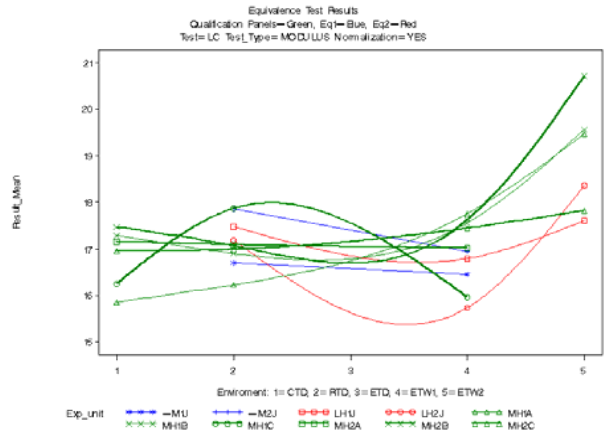
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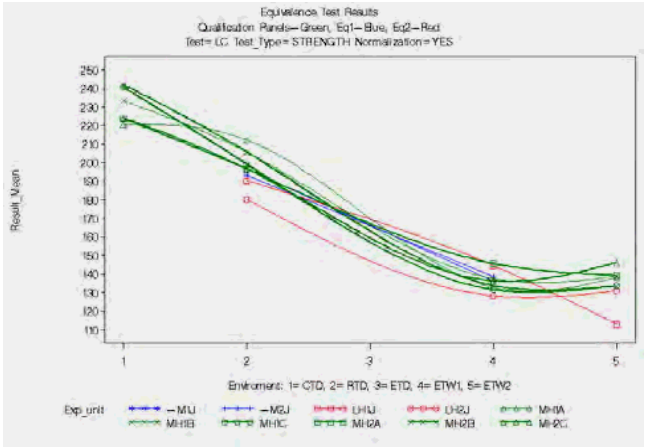
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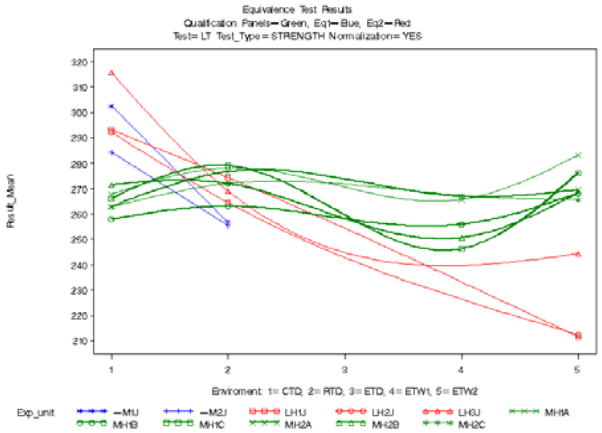
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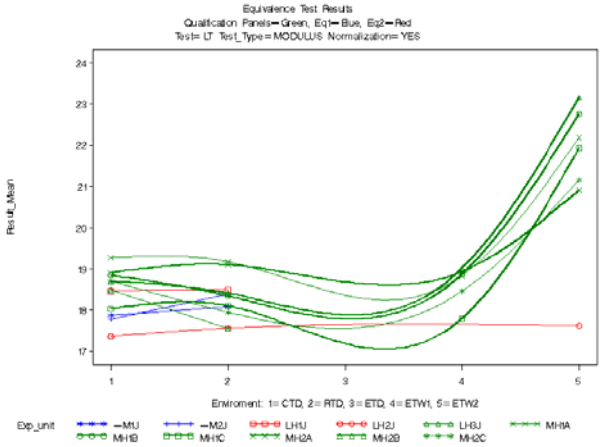
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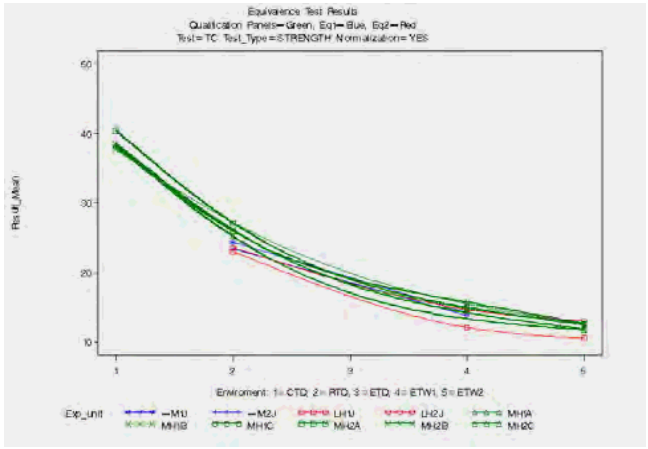
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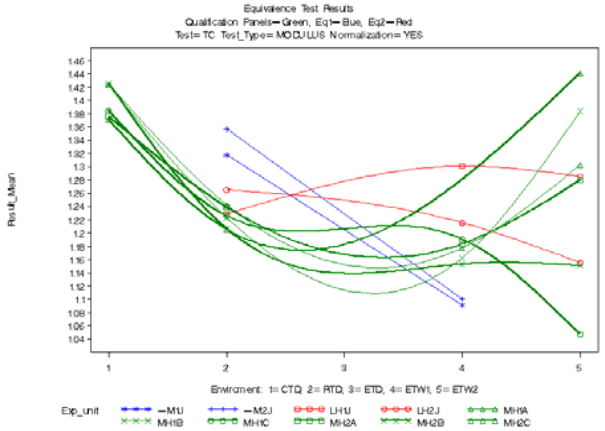
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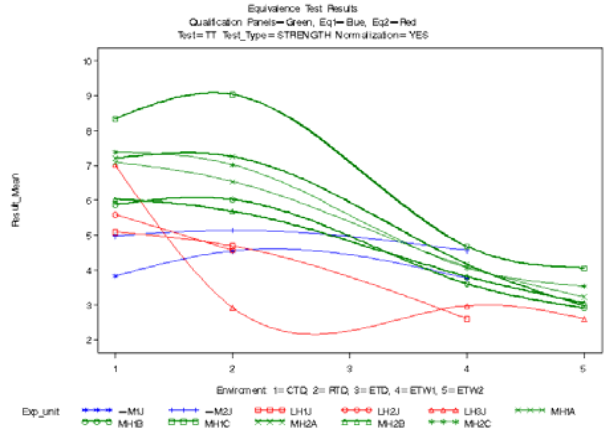
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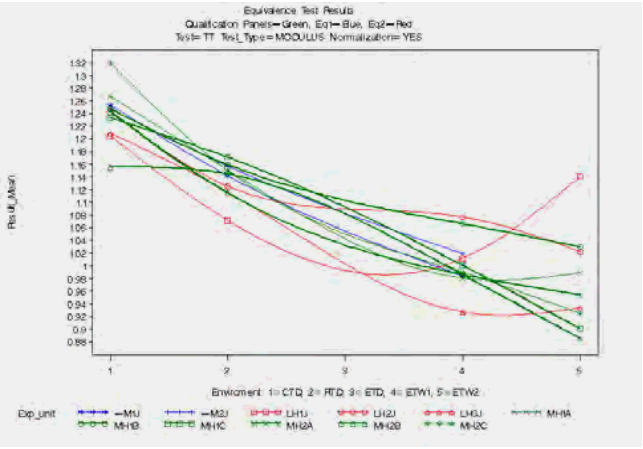
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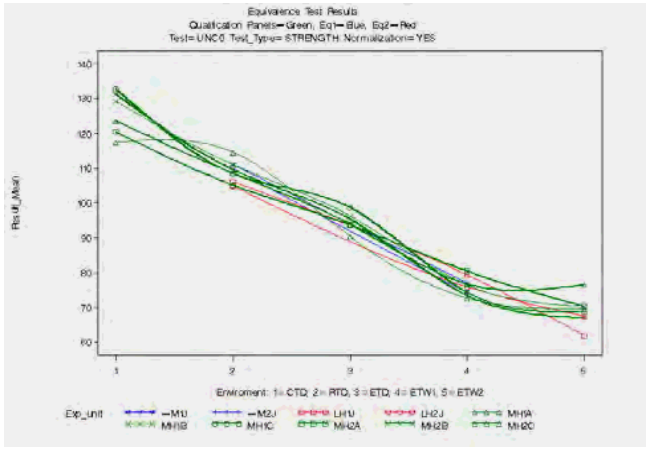
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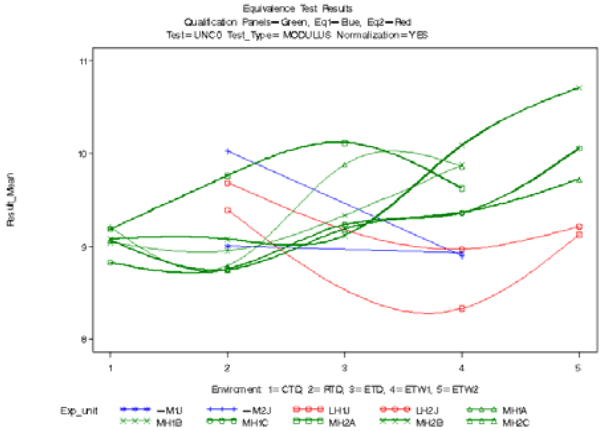
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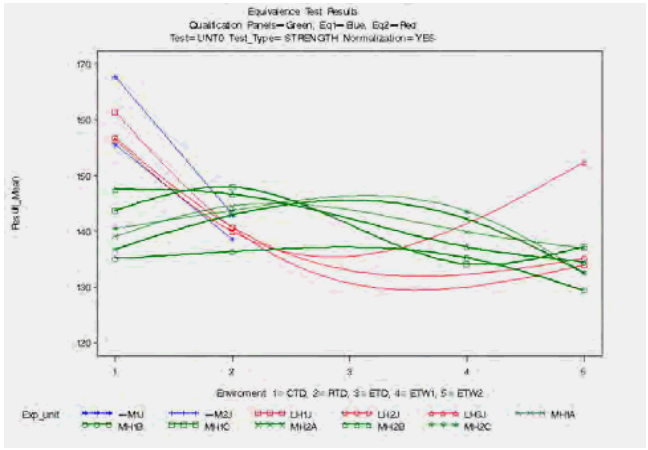
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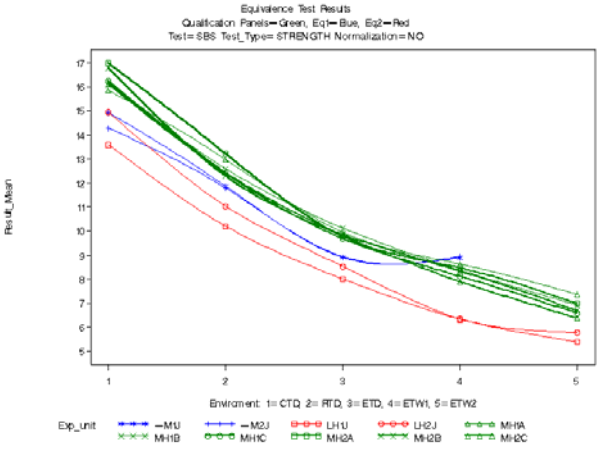
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Proposed Approach

Multivariate Equivalence Testing

- Multivariate – looking at all the test results simultaneously along with the correlations
- Equivalence Testing – setting up the null hypothesis as “these populations are different” rather than “these populations are the same”.
- Neither of these approaches alone have been fruitful in this type of application, but a combination of the two has potential.

Brief Review

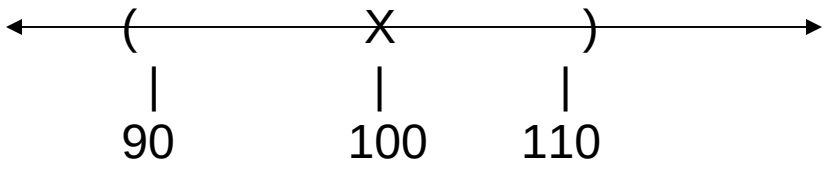
- Current Approach
- Confidence Intervals – a measure of the ‘fuzziness’ or uncertainty of a statistic.
- Hypothesis testing – Traditional and Equivalence

Current Equivalency Testing

- Are new samples ‘equivalent’ to the qualification material?
  - Our statistics only tell us about one test at a time.
  - We know that some failures can be expected due to chance alone,
- Engineering judgment must be used to make the determination of overall equivalence

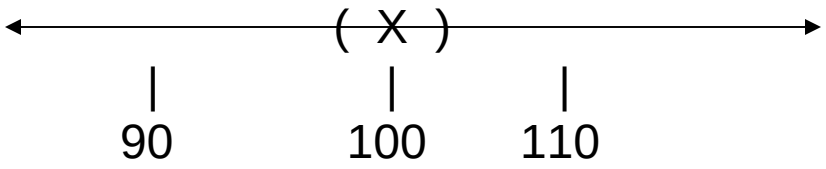
Confidence Intervals

- The interval around a sample statistic that we can be relatively ‘confident’ contains the true value. It is a way of gauging the uncertainty around our sample value.
- For example, the mean of particular attribute, such as compressive strength, might be 100 with a 95% confidence interval be from 88.7 to 111.3

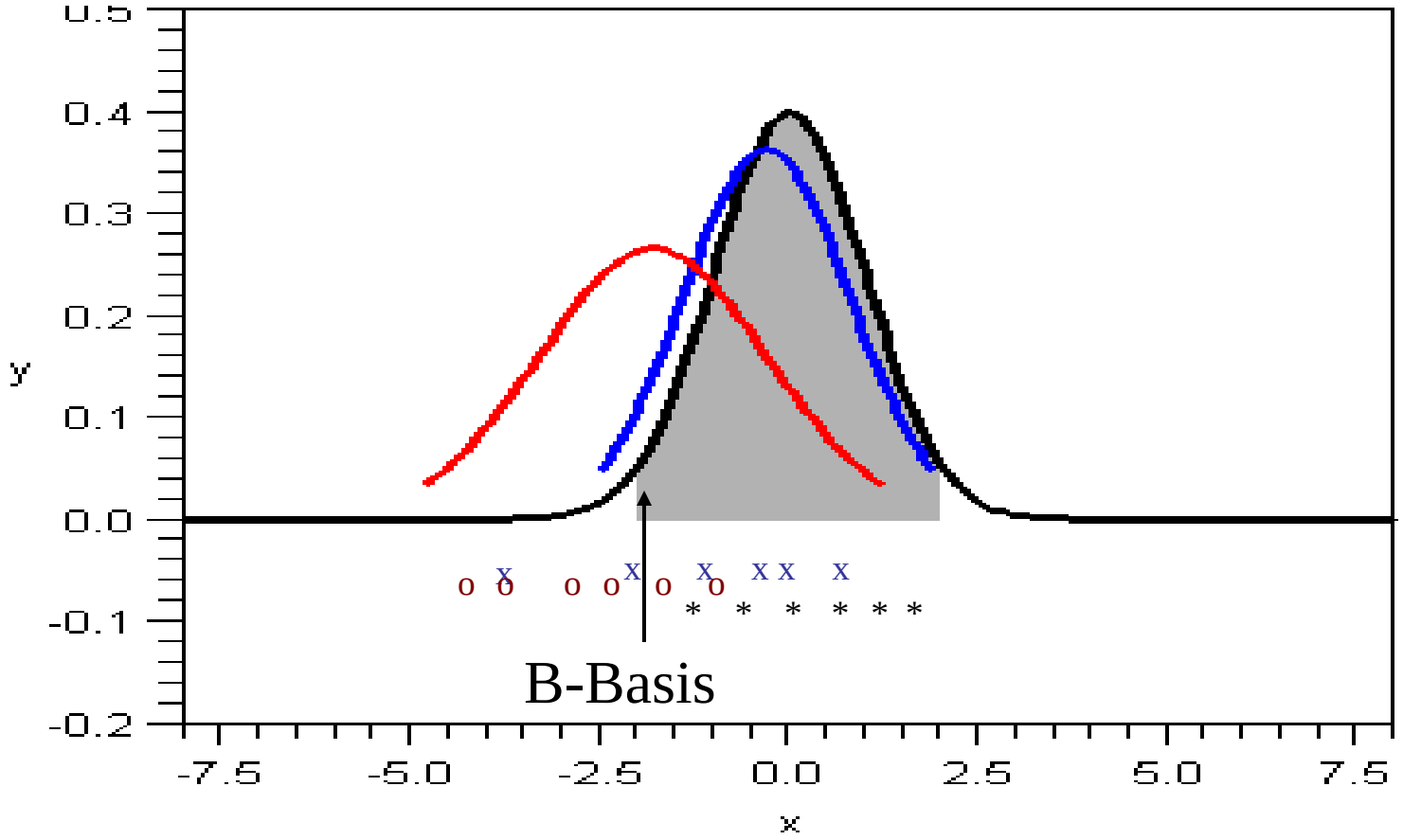


Confidence Intervals

- As expected, the larger the sample used to compute the statistic, the less uncertainly and the smaller the interval around it.
- For example, with a larger sample, a mean of 100 might have a 95% confidence interval from 98.4 to 101.6



Hypothesis Testing: The same or different?



Hypothesis testing

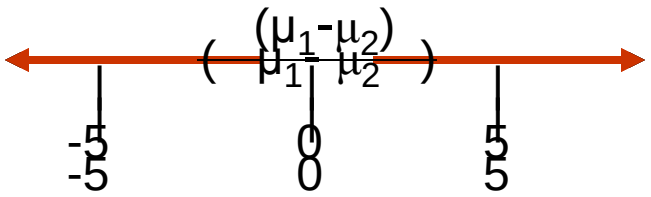
Two Sided Hypotheses (modulus)

$$H_0 : \mu_1 - \mu_2 = 0 \qquad H_1 : \mu_1 - \mu_2 \neq 0$$

One Sided Hypotheses (strength)

$$H_0 : \mu_1 - \mu_2 \leq 0 \qquad H_1 : \mu_1 - \mu_2 > 0$$

- Null Hypothesis:
  - What we assume true
  - Must contain equality



- Alternative Hypothesis: What we want to prove true. Reject the null when the sample statistics lies in the red area.
- As the sample size increases, the confidence interval decreases and the rejection region increases.

Current Equivalency Testing

Two Sided Hypotheses (Modulus)

$$H_0 : \mu_1 - \mu_2 = 0 \qquad H_1 : \mu_1 - \mu_2 \neq 0$$

One Sided Hypotheses (Strength)

$$H_0 : \mu_1 - \mu_2 \leq 0 \qquad H_1 : \mu_1 - \mu_2 > 0$$

- The null hypothesis assumes there is no difference between the two samples (two-sided) or that the equivalence sample mean is greater than or equal to the original qualification sample mean (one-sided).
- We reject the assumption of less than or equal by testing the mean and the minimum of the sample against their expected values (one-sided test).
- We reject the assumption of equality if and only if the new sample mean is significantly different than expected (two-sided test).

Problems with Current Method

1. We assume equality as the null and then try to prove that assumption false. The probability of making the correct decision to *accept* the null hypothesis is unknown, but will be substantially lower than the confidence level which gives the probability of wrongly *rejecting* the null.
2. As the sample size increases, the acceptance region for the null hypothesis (equivalence) grows smaller.
3. Because so many tests are performed and some failures are to be expected (5% of incorrectly finding difference), subjective judgment must be used to determine if the material can be considered equivalent.

Solutions to Problems

Problems 1 and 2 can be dealt with through hypothesis testing of equivalence.

Problem 3 can be solved using multivariate testing.

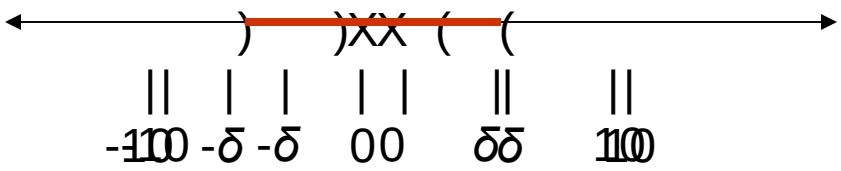
These approaches have their own issues and constraints which have prevented their use prior to this.

An integrated approach using both methods will be useful but MUST be implemented in conjunction with setting basis values

Equivalence Hypothesis

$$H_0 : |\mu_1 - \mu_2| \geq \delta \qquad H_1 : |\mu_1 - \mu_2| < \delta$$

- The null hypothesis assumes a difference (δ) exists. When the null is rejected, the alternative is accepted at the specified level of confidence.
- Recall:
  - Null Hypothesis is what we assume and **must** contain equality
  - Alternative Hypothesis is what we want to prove true.
- Reject the null and accept the alternative when the sample mean lies in the red area.



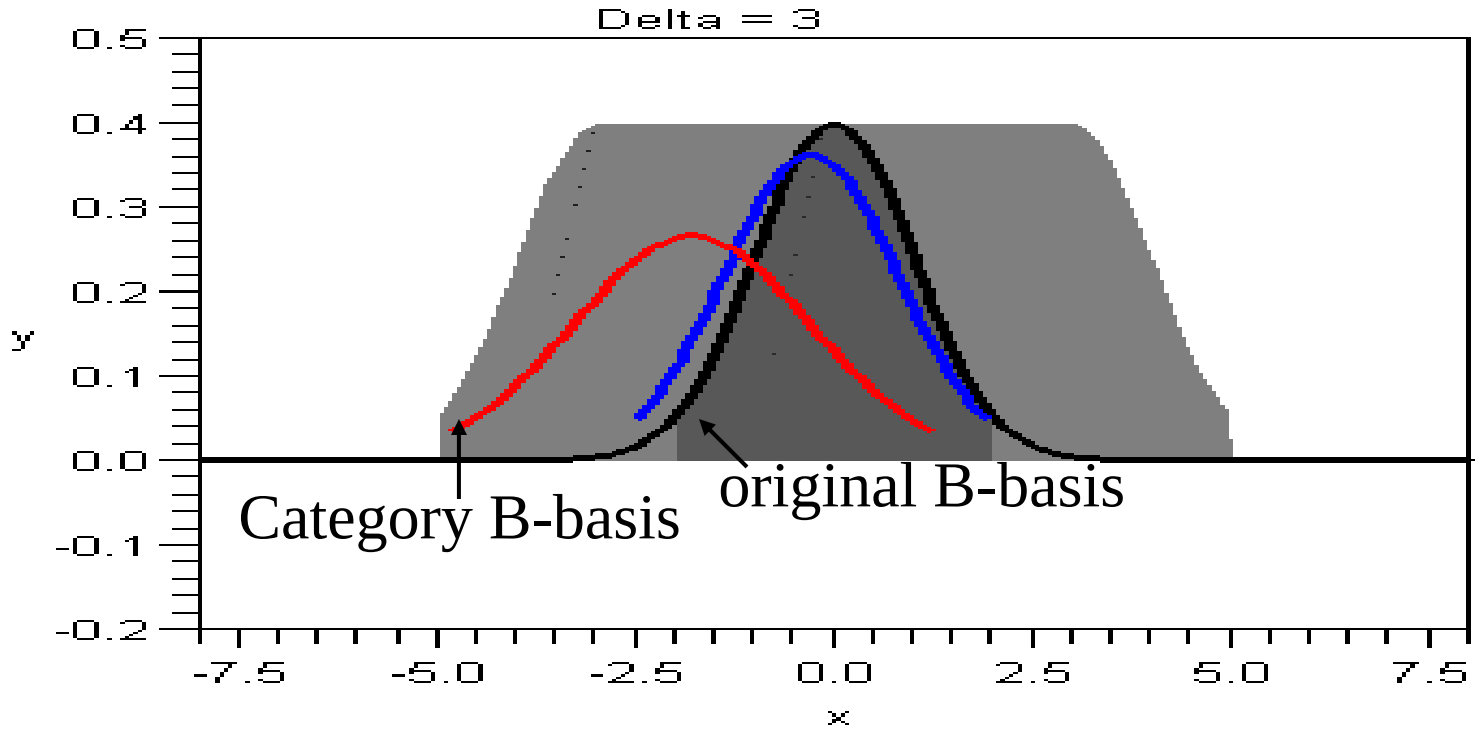
- Acceptance region increases with sample size

Why hasn't equivalence testing been used previously?

- Equivalence testing requires δ to be defined **prior** to setting basis values. Thus, the concept of equivalence testing has be in place from the beginning.
- Problem: Basis values will be lowered by δ.
  - In order to use this method, basis values **must** be computed assuming a sample mean at the edge of the acceptable zone: $\mu - \delta$.

Equivalence Testing

- Acceptance region for the example shown earlier with delta = 3σ:



Multivariate Hypothesis Tests

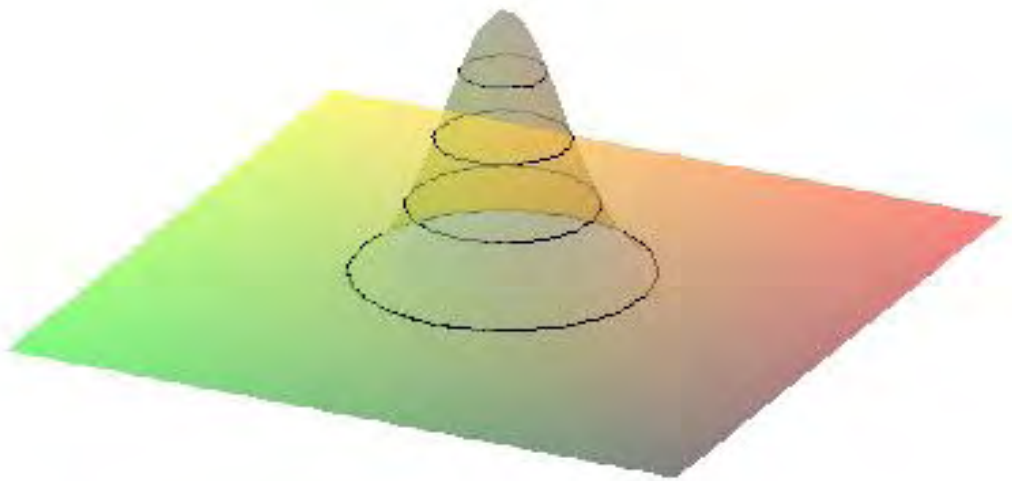
- Problem 3, the issue of needing to use subjective judgment to determine if the material can be considered equivalent given all test results, can be solved with a multivariate analysis
- We can set the confidence level at 95% and only perform a single test.

Multivariate Hypothesis tests

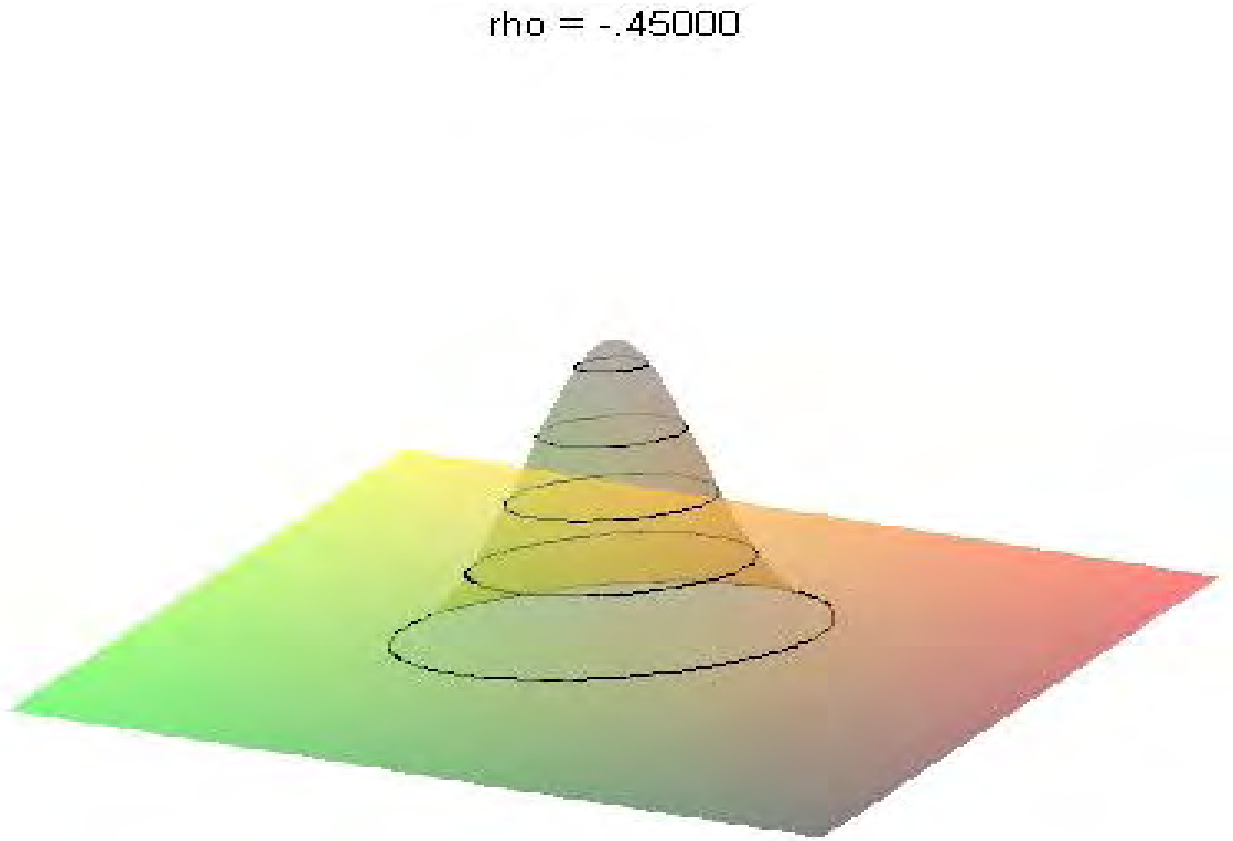
- Plus:
  - Takes correlation between characteristics into account
  - Sensitive to small differences between groups.
- Minus:
  - A multivariate test will fail nearly 100% of materials tested for equivalence.

Bivariate normal distribution with no correlation

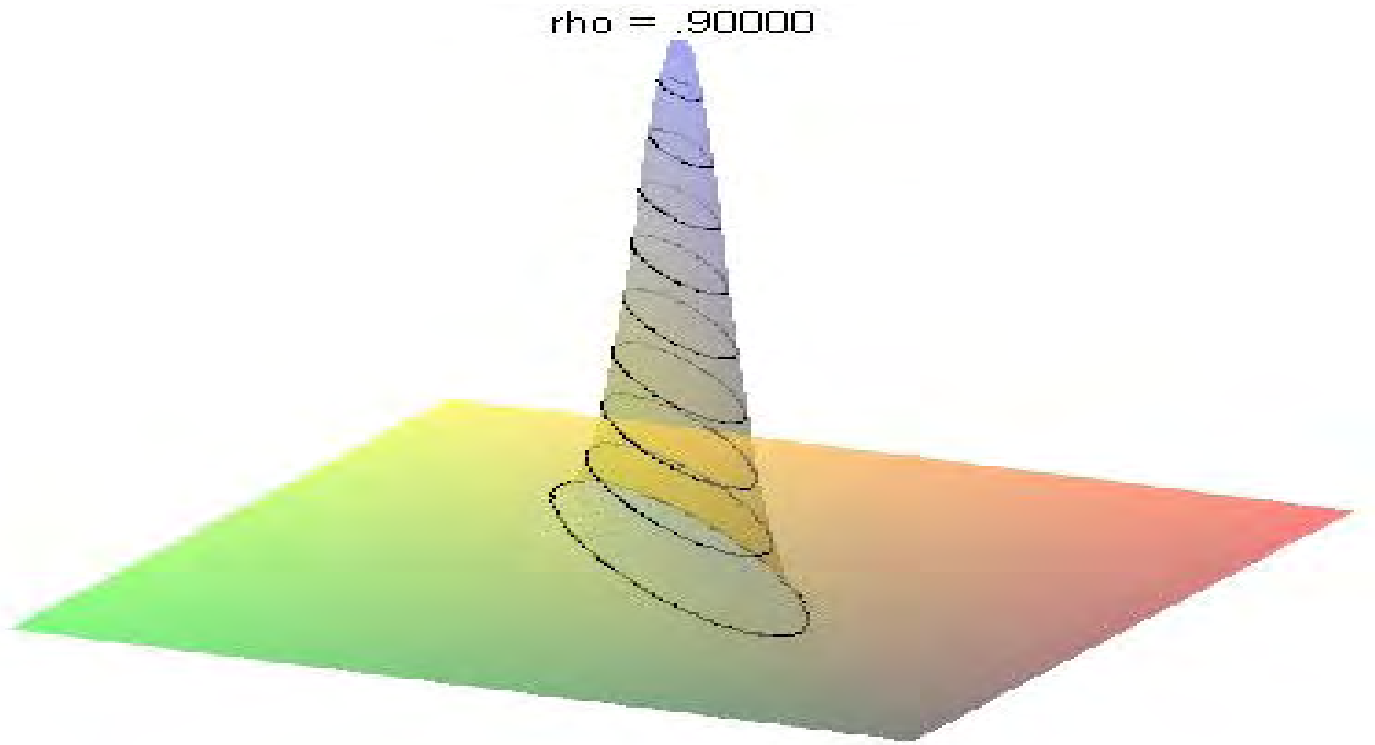
rho = 0.



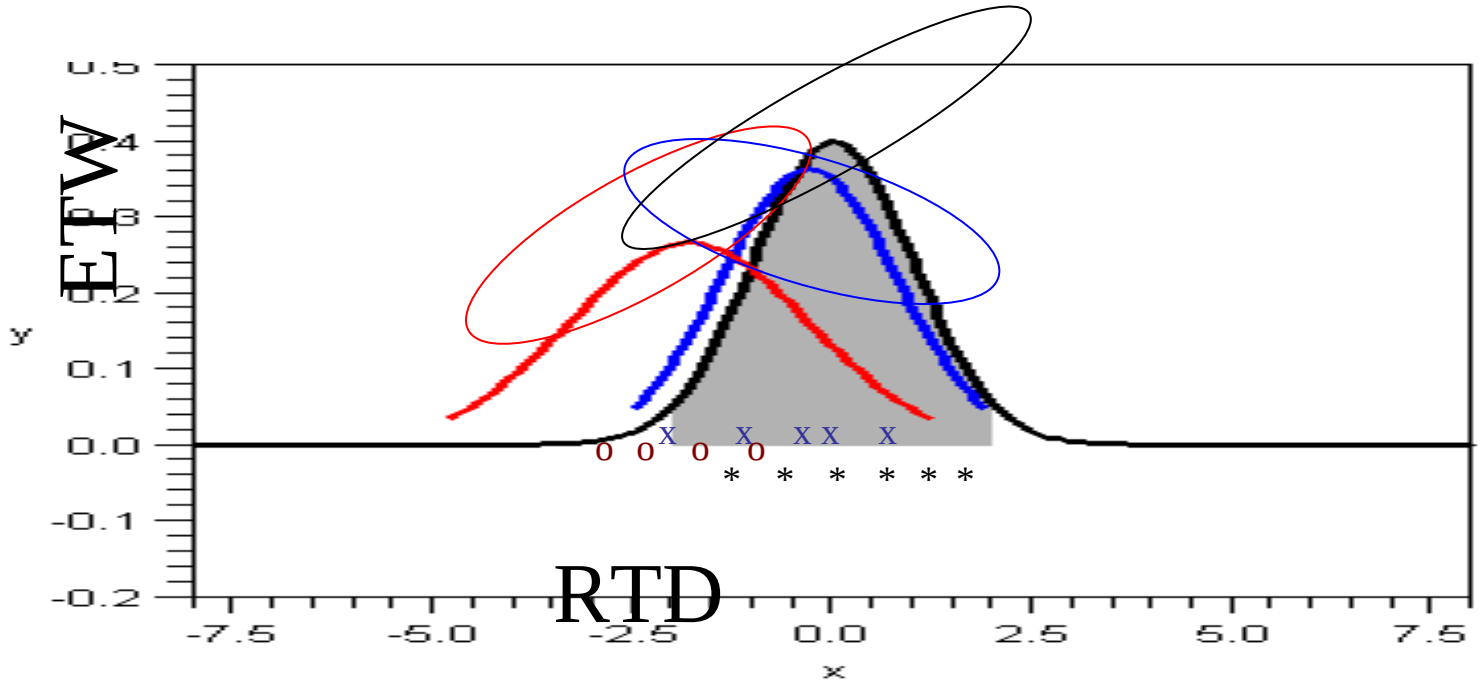
Bivariate normal distribution with moderate correlation



Bivariate normal distribution with strong correlation



Multivariate Hypothesis Testing



Traditional Multivariate Hypothesis Testing

Independent variables

Correlated variables

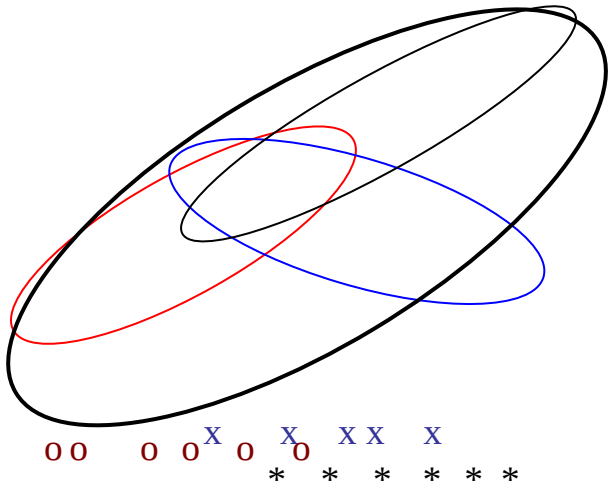
- As the sample size increases and the number of tests increase, the region for acceptance of equivalence gets smaller. We can better discern even tiny differences between two samples. We can identify statistically significant differences that are of no practical concern.

Problem with Multivariate Approach

- **Every sample of material is little bit different from every other sample. If any one of the single characteristic tests failed, then the multivariate test will also fail.**
- **A test that always gives the same result – failure – is not useful. We don't care if the materials are not exact clones but we do need assurance that the basis values are met.**

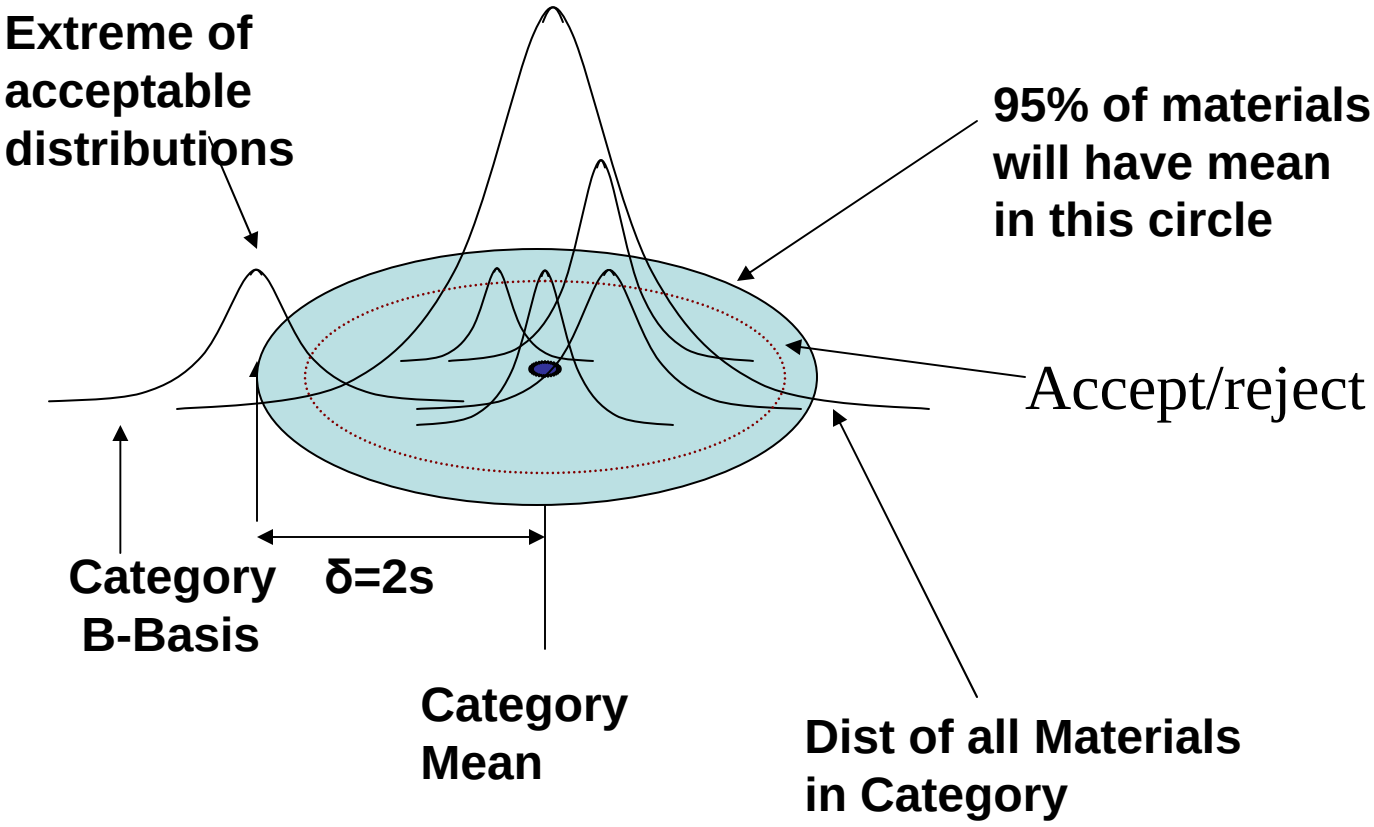
Equivalence Multivariate Testing

ETW



RTD

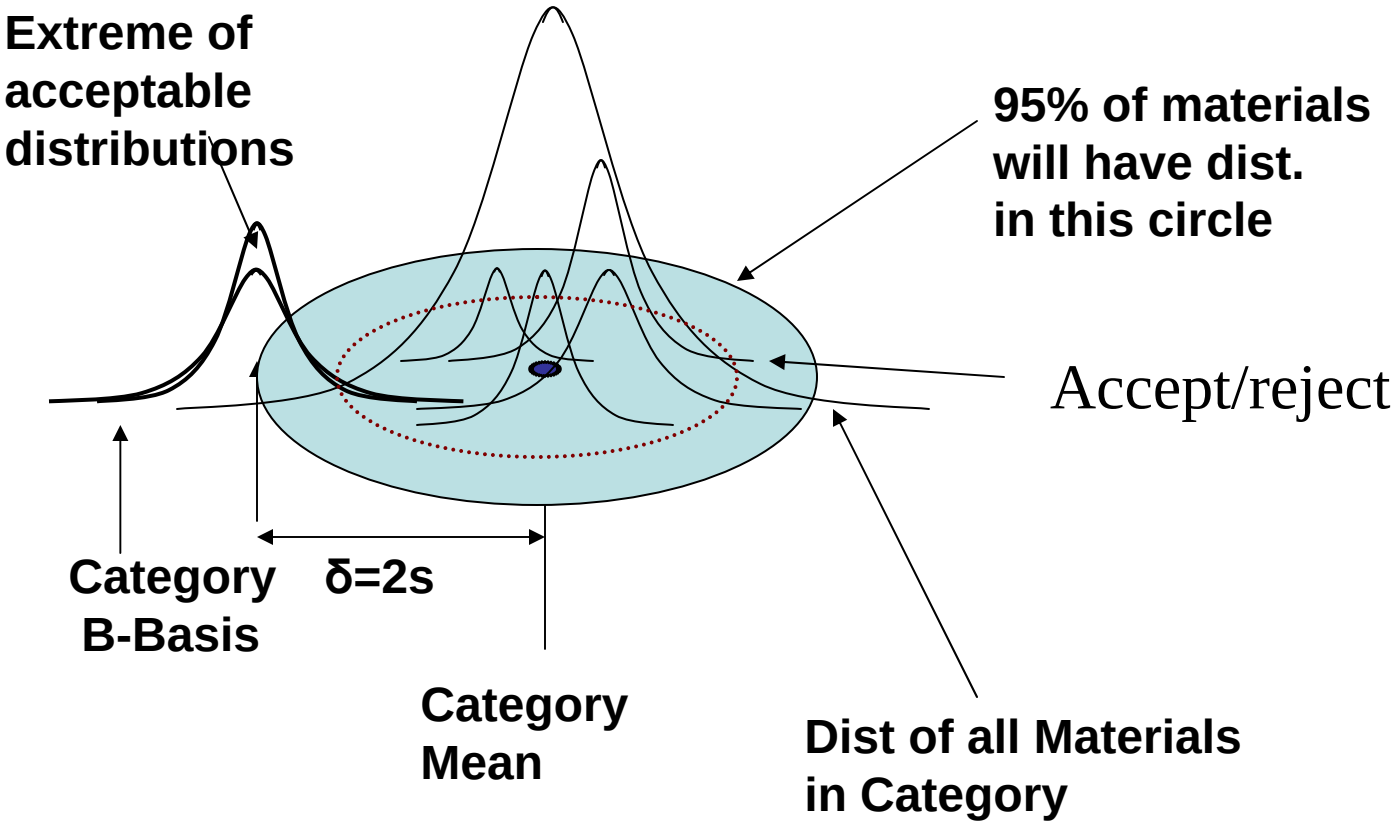
Computing Category Basis values using Equivalence Approach



Advantages of this approach

- We can control both the type I AND type II errors (producer's and consumer's risk) though setting delta as well as alpha
- As our database grows to include more samples of more materials, estimates of the within batch and batch-to-batch variation will improve. As a result, A- and B-basis values for categories can be revised upward over time. **Any such revisions can be retroactively applied to all materials included in that category**.

Effect of increasing sample size



With an adequate database of test results for composite materials:

- A single objective measure of how different a new material recipe is compared to the original recipe.
- Basis values developed with the new methodology would apply to all materials within a category
- Grades of materials could be nested within categories – Unitape Grade A, Plain Weave Grade D, etc.
- Ability to create a system allowing designers to create categories by defining individual delta values that are based on the requirements for a particular application and then determine which materials will fall into that category

Integrating two approaches

- Because this new approach will require extensive data to develop, our traditionally computed basis values for individual materials will still be needed and used.
- The shared database can be used for tracking the data from different materials. The basis values and acceptance criteria for categories may start out low, but as more data is available, the acceptance criteria, spec limits, basis values, etc. can be adjusted.

Underlying Mathematics

- Applying the techniques of equivalence testing to a multivariate analysis is not well developed beyond the bivariate normal case.
- Currently working on the extension of this theory to the multivariate normal distribution.

A Look Forward

- Benefit to Aviation
  - Provides solution and guidance to the industry
  - Documents lessons learned
  - Ensures a supply of composite materials with stable properties
- Future needs
  - Continue to work with the industry on material and process issues
    - Develop other essential guidance documents such as Carbon Fiber PCD Preparation Guide