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GRR (gauge repeatability & reproducibility) Analysis of Effects of Measurement Queue Time on SiO_2 Thickness

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GRR (gauge repeatability & reproducibility) Analysis of Effects of Measurement Queue Time on SiO_2 Thickness

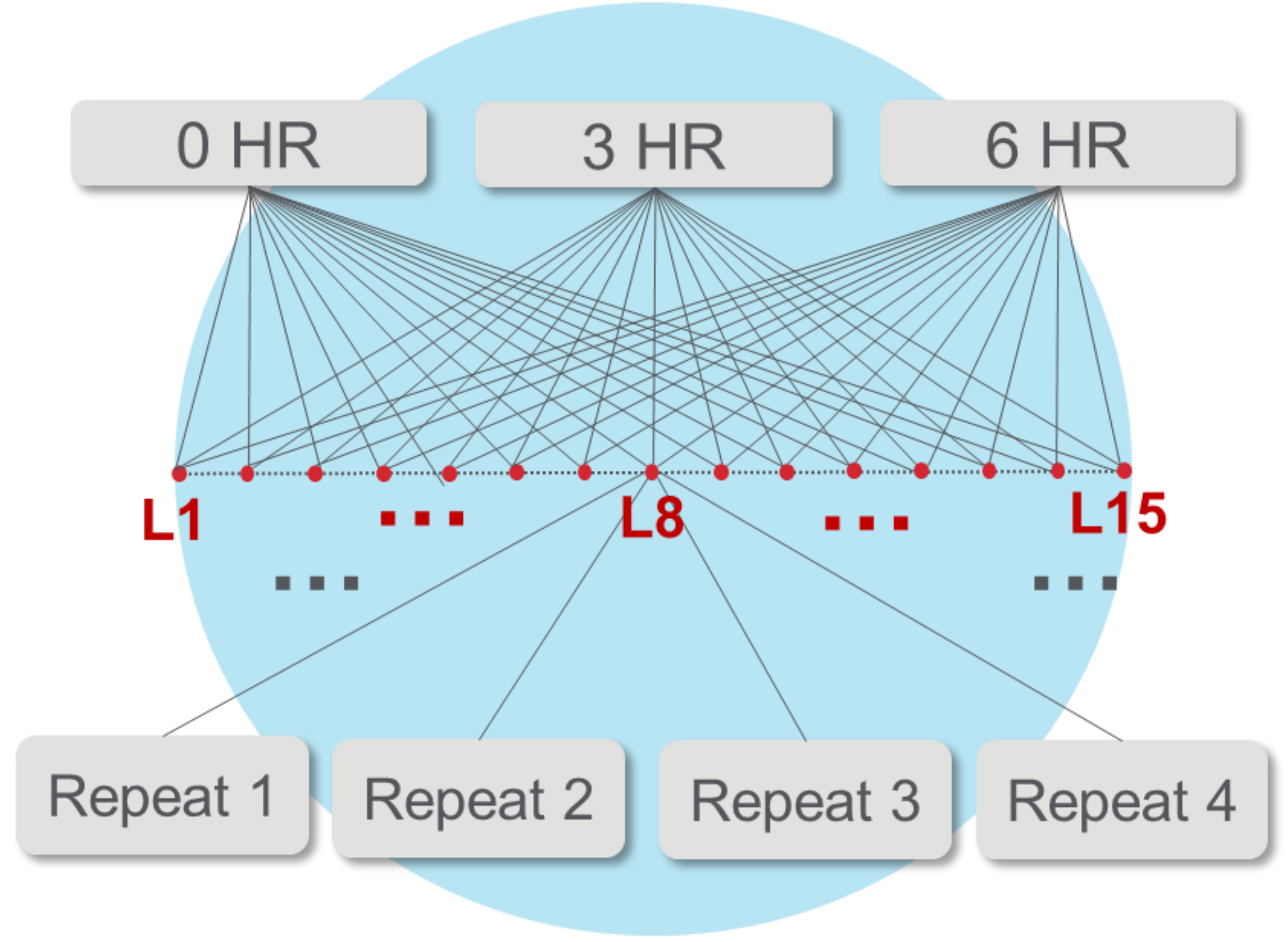
Introduction

- In chip production, process engineers rely on metrology tools to monitor and optimize layer properties against facility changes, tool hardware decay and wafer variations. To ensure accurate measurement results, metrology capability should be evaluated based on gauge repeatability and reproducibility (GRR).
- **Unlike usual GRR methods, this project takes measurement queue time as reproducibility factors and investigates the effects on SiO_2 thickness results.** It can be further applied to assist critical queue time control and measurement improvement in wafer fabrication.

Methods & Objectives

GRR analysis of thickness measurement follows the flow as shown below:

- **Data collection**: SiO_2 thickness data were collected based on MSA design
- **GRR performance evaluation**: 4 success criteria of GRR performance are compared; main effect and crossed GRR models are conducted to assess P/T ratio, interaction effects and misclassification risks
- **Xbar-S Chart analysis for GRR root cause analysis**: repeatability and reproducibility variations are studied to improve GRR performance from metrology tool, sample selection and queue time effects
- **Figure of Merits for process capability simulation**: current process capability and future improvement plan are discussed



Results

GRR Success Criteria and Performance Evaluation

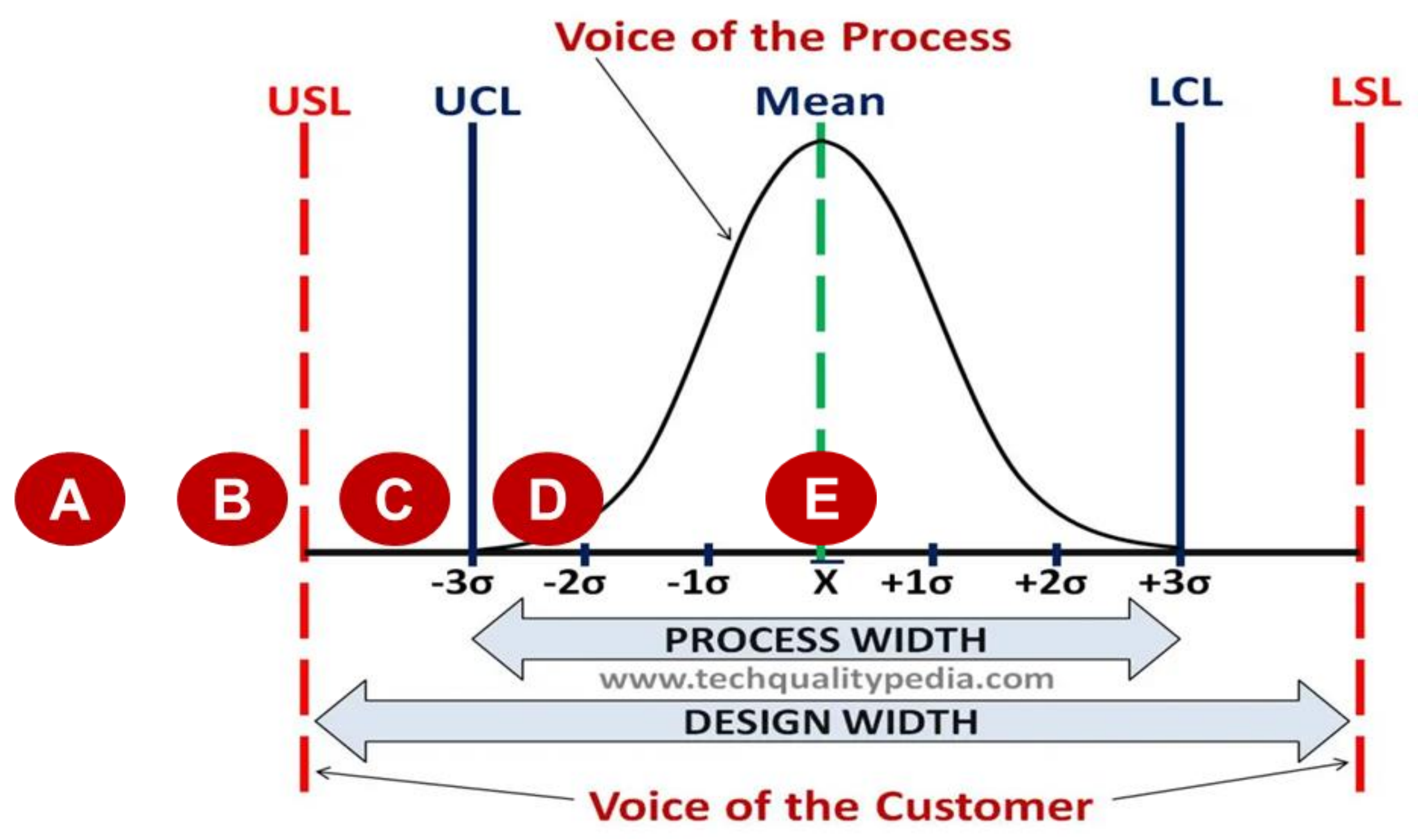
P/T Ratio Referred to Tolerance (USL-LSL)

P/TV Ratio Referred to Gauge Samples

Which One?

P/V Ratio Referred to Process (UCL-LCL)

P/M Ratio Referred to Modeling (RMSE)



GRR Root Cause Analysis

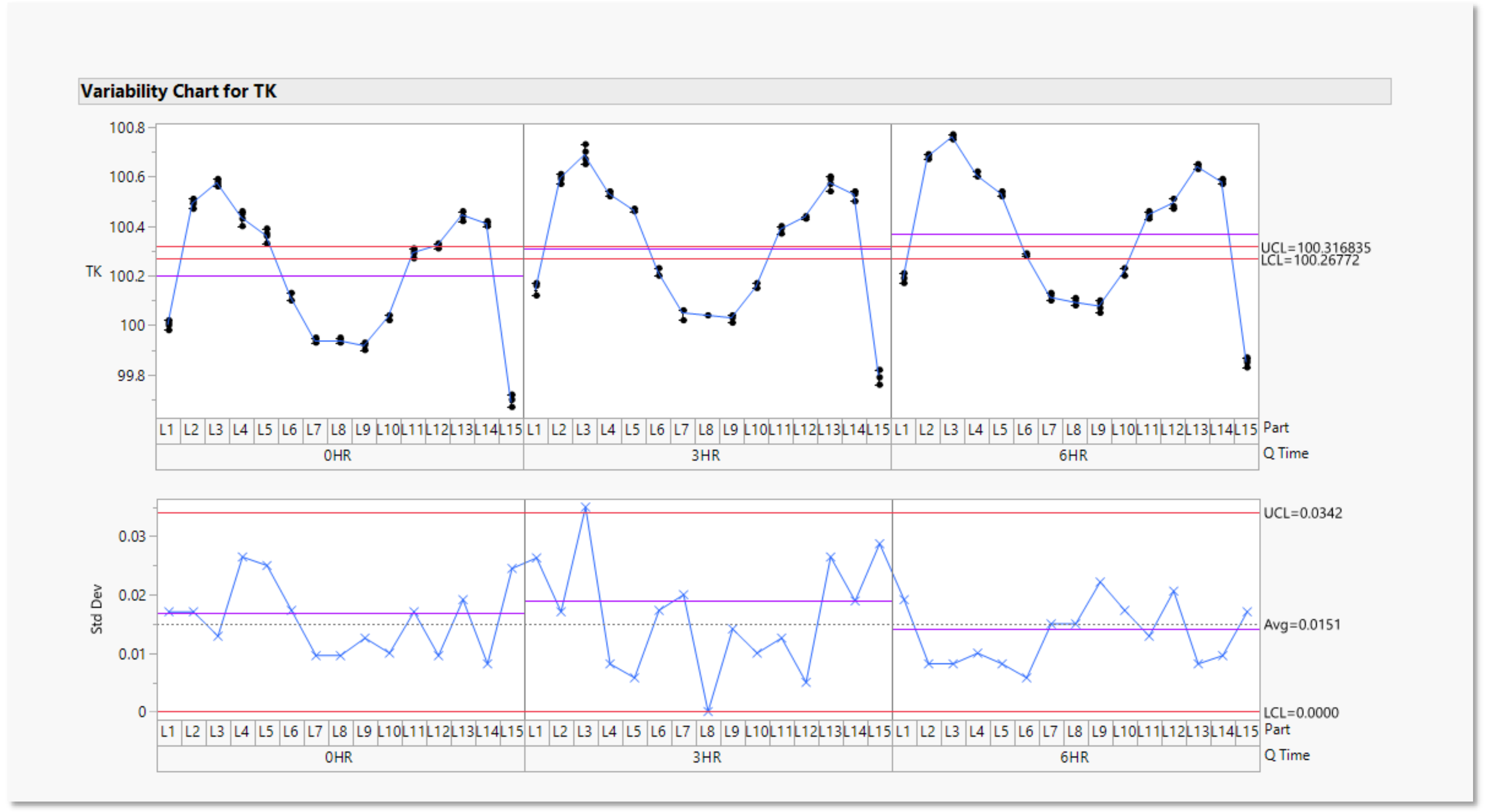
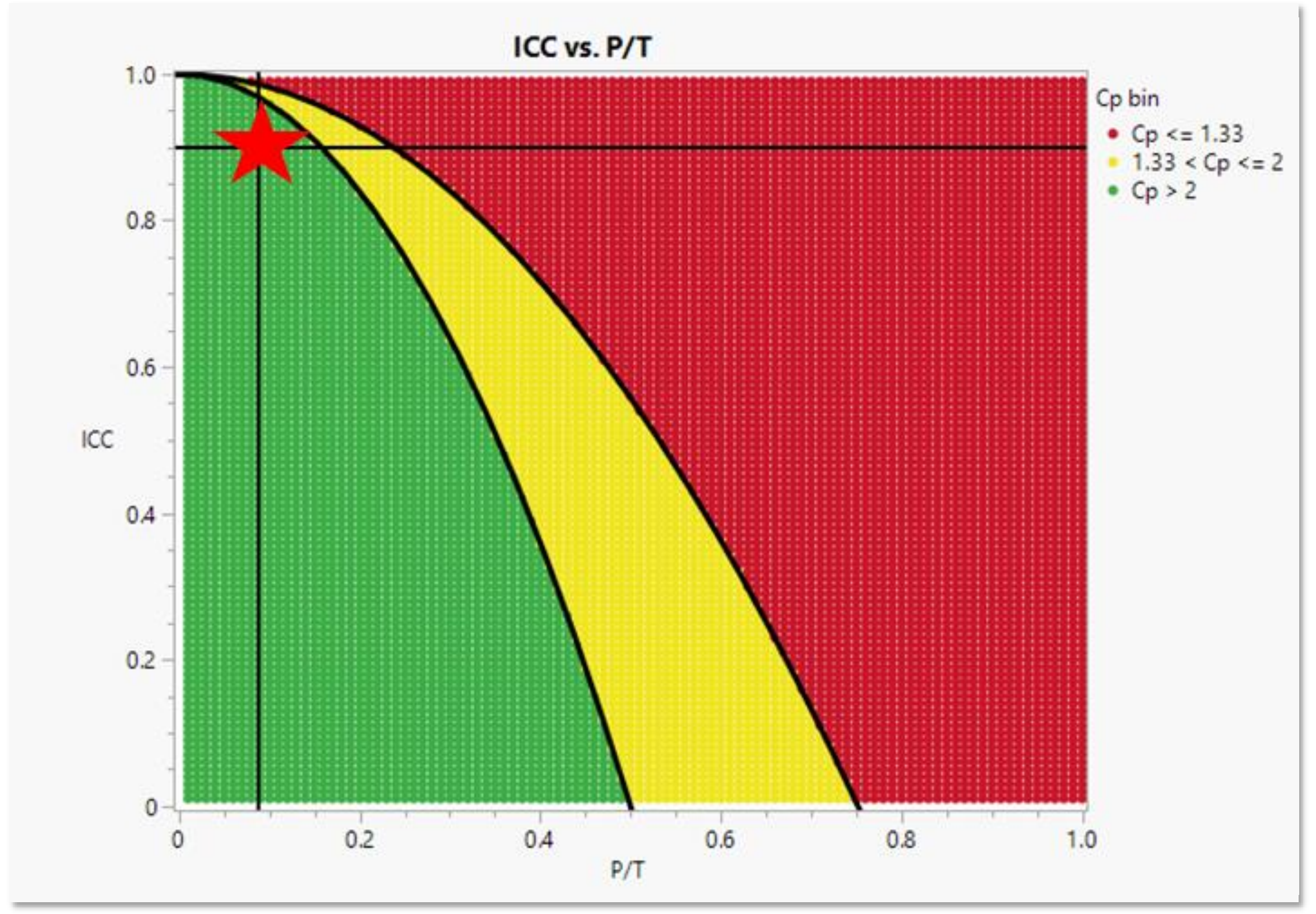


Figure of Merit: ICC, P/T and Process Capability



Conclusions

In this project, ellipsometry measurement capability is adequate within 6 hours after SiO_2 generation. Measurement is stable, and the metrology tool can differentiate between different parts. Based on the current GRR capability, we can tighten the tolerance by 40% with a competitive P/T ratio of 15%. With the help of the JMP platform, this project demonstrates a quick GRR analysis flow for queue time control workflow in wafer fabrication, and evaluation and improvement of metrology capability in semiconductor industry.

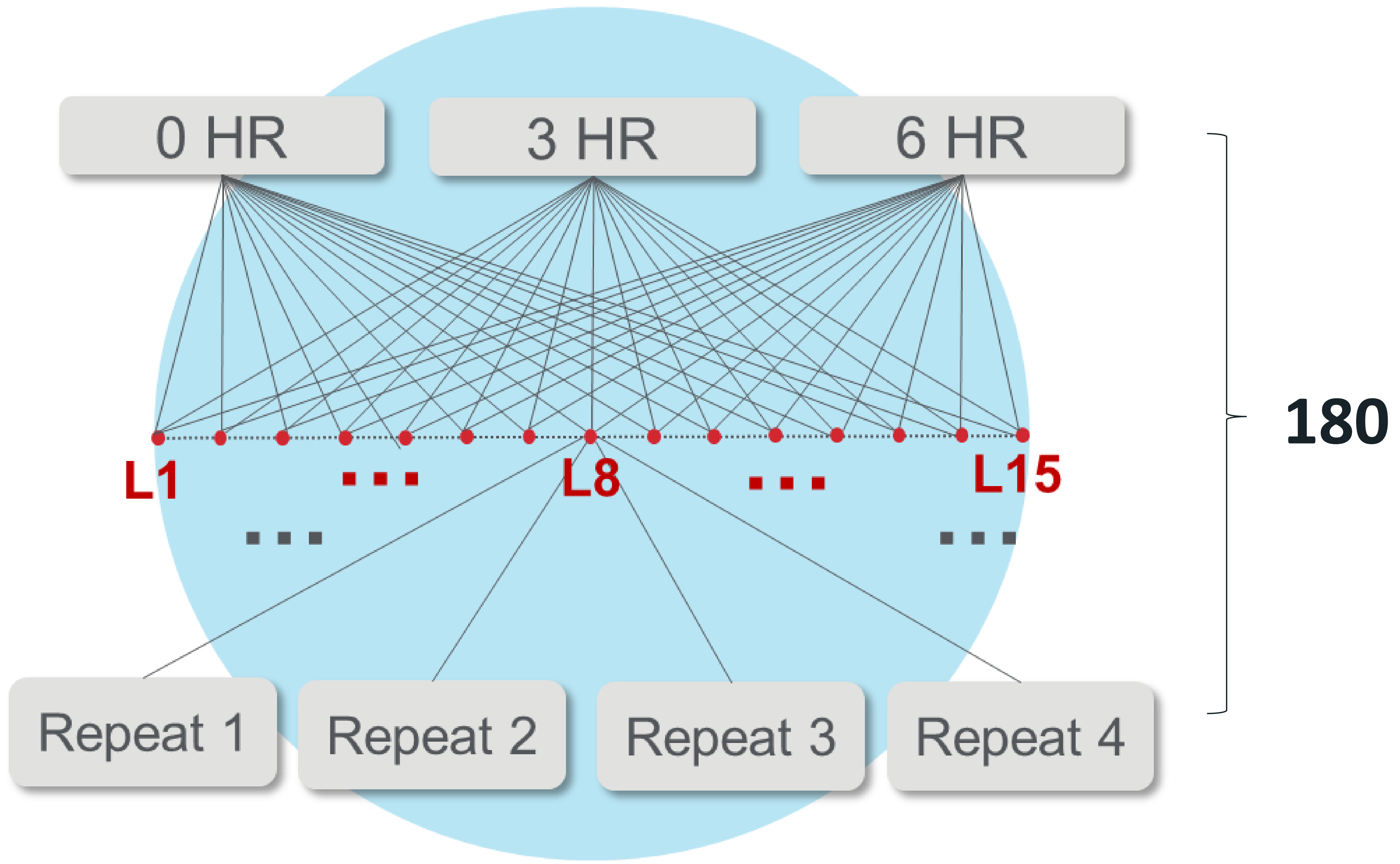
References & Acknowledgements

Thanks to Charles C Chen and Wayne Chou for mentoring and technical support for this project!

Thanks to Applied Materials China Management Team for the great support for the JMP program!

GRR Data Sampling

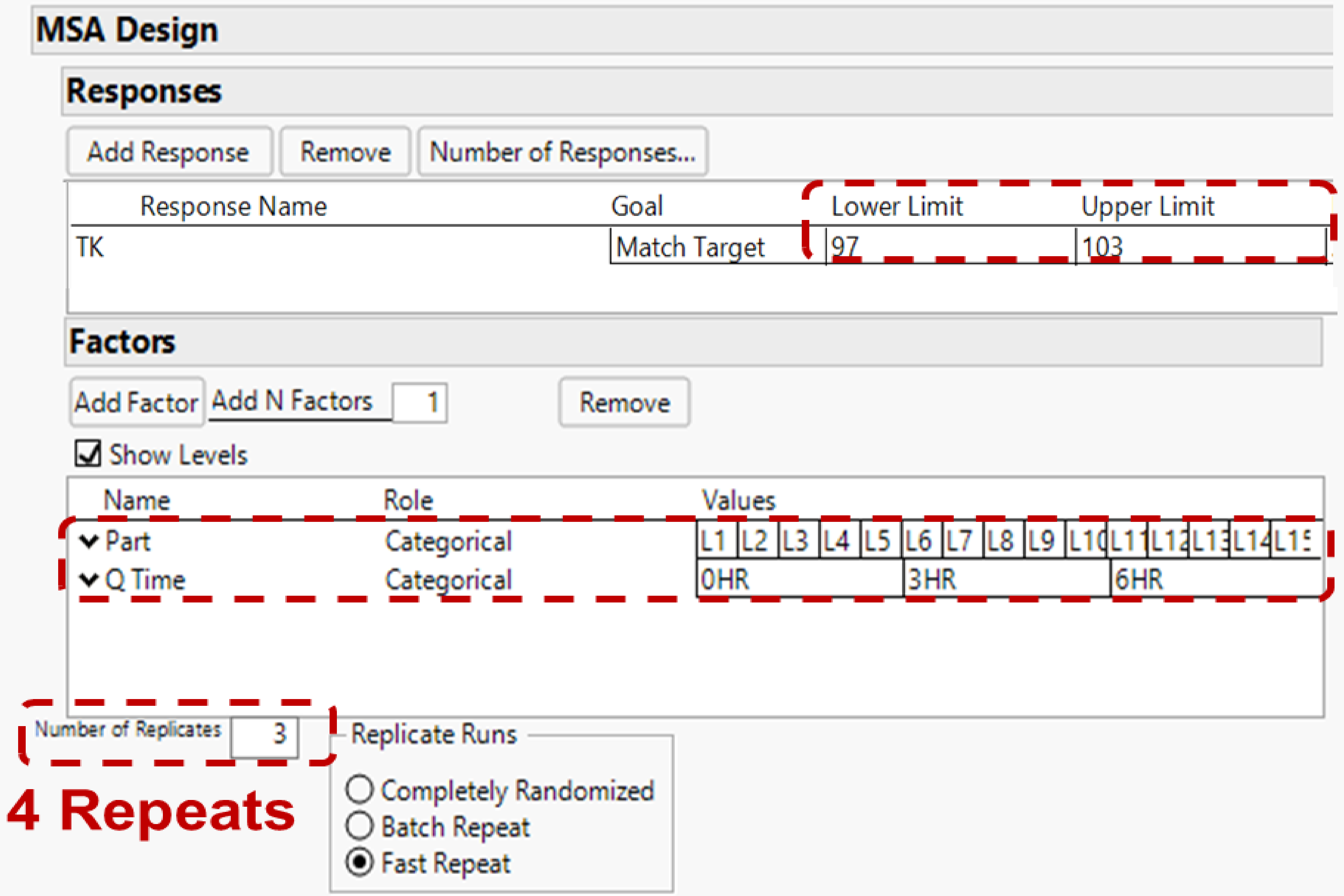
1. Sampling Plan



Repeats: No Part handling
Replicates: Part handling

- Part: 15 parts ~ 15 coupons from a SiO_2 wafer
- Repeatability: **4 repeats** for one part one time
- Reproducibility: **0 & 3 & 6** hour
- Tolerance spec: **LSL-USL = 97-103 Å** for each part

2. MSA Design and Data Collection



Response Name	Goal	Lower Limit	Upper Limit
TK	Match Target	97	103

Add N Factors 1

☑ Show Levels

Name	Role	Values
Part	Categorical	L1 L2 L3 L4 L5 L6 L7 L8 L9 L1 L1 L1 L1 L1 L1
Q Time	Categorical	0HR 3HR 6HR

Number of Replicates 3

4 Repeats

Replicate Runs
○ Completely Randomized
○ Batch Repeat
● Fast Repeat

Rules for Fast Repeat

- Sequence following Queue time (0,3,6)
- 15 parts at the same Queue time
- 4 repeats within the same Part

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GRR Success Criteria and Performance Evaluation

1. GRR Success Criteria

P/T Ratio Referred to Tolerance (USL-LSL)

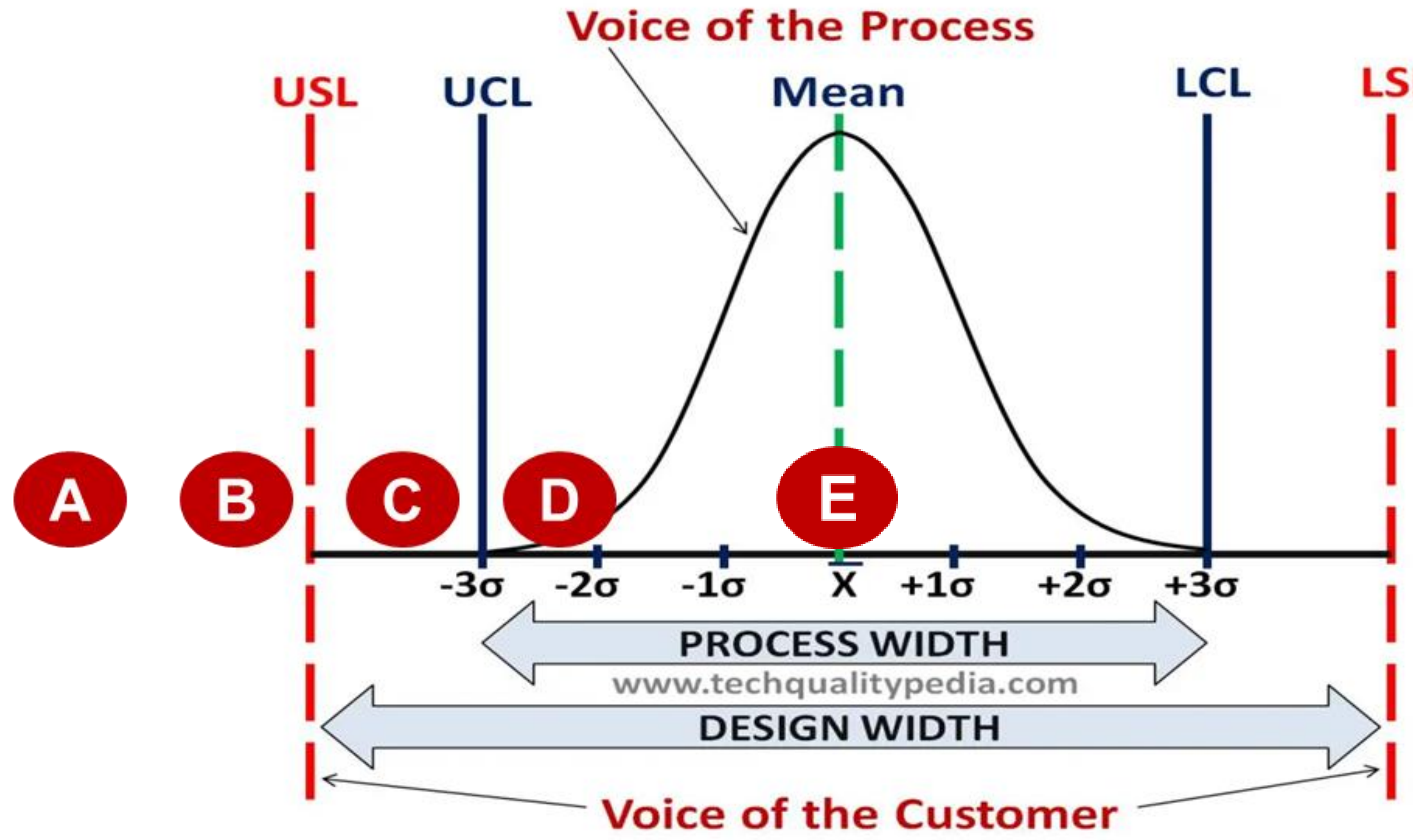
P/TV Ratio Referred to Gauge Samples

Which One?

P/V Ratio Referred to Process (UCL-LCL)

P/M Ratio Referred to Modeling (RMSE)

2. Misclassification Risk

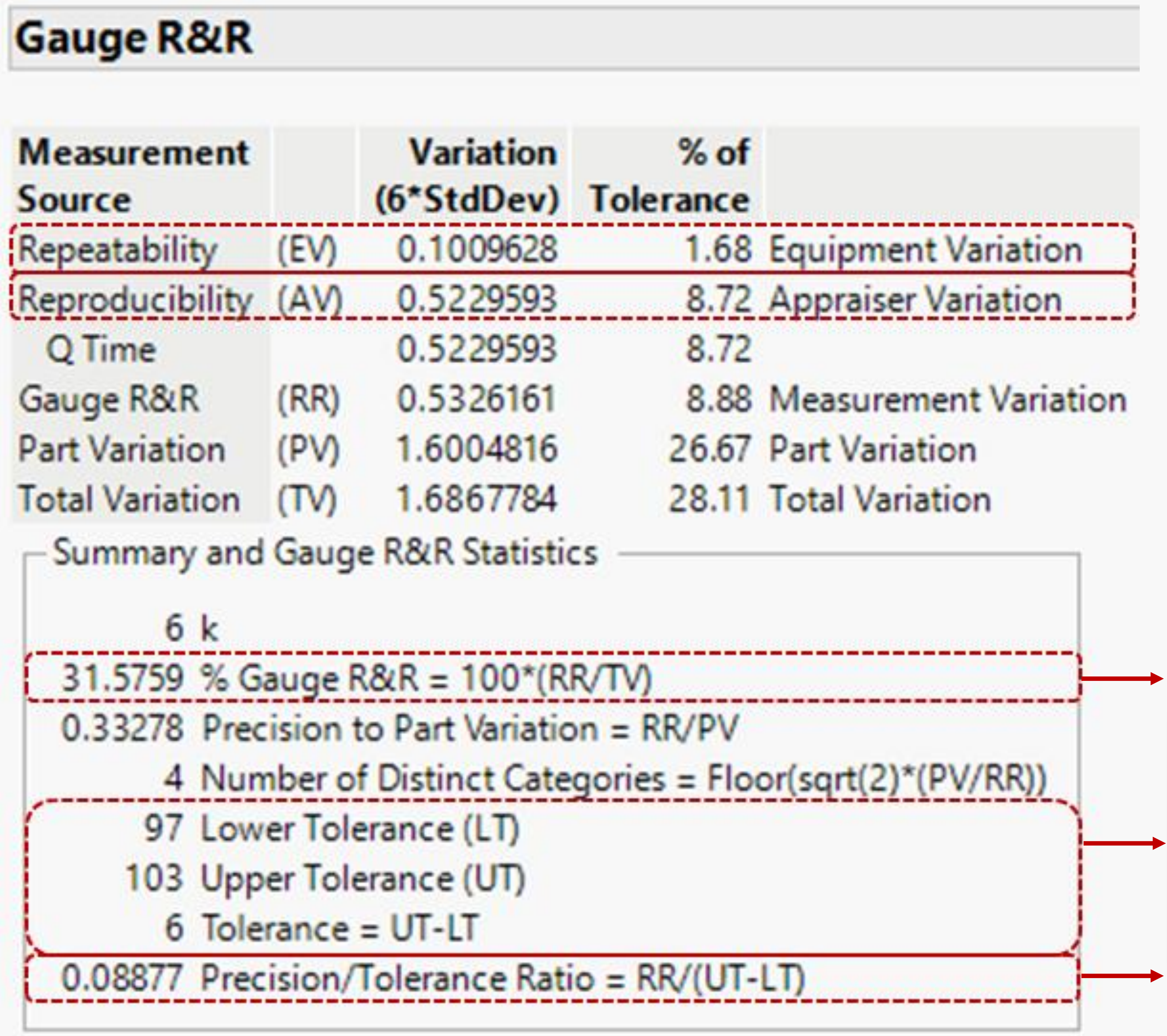


Alpha risk: Producer Risk

Beta risk: Customer Risk

3. GRR Performance Evaluation of Thickness Measurement under Queue Time Effects

3.1 Main Effect GRR (w/o interaction)



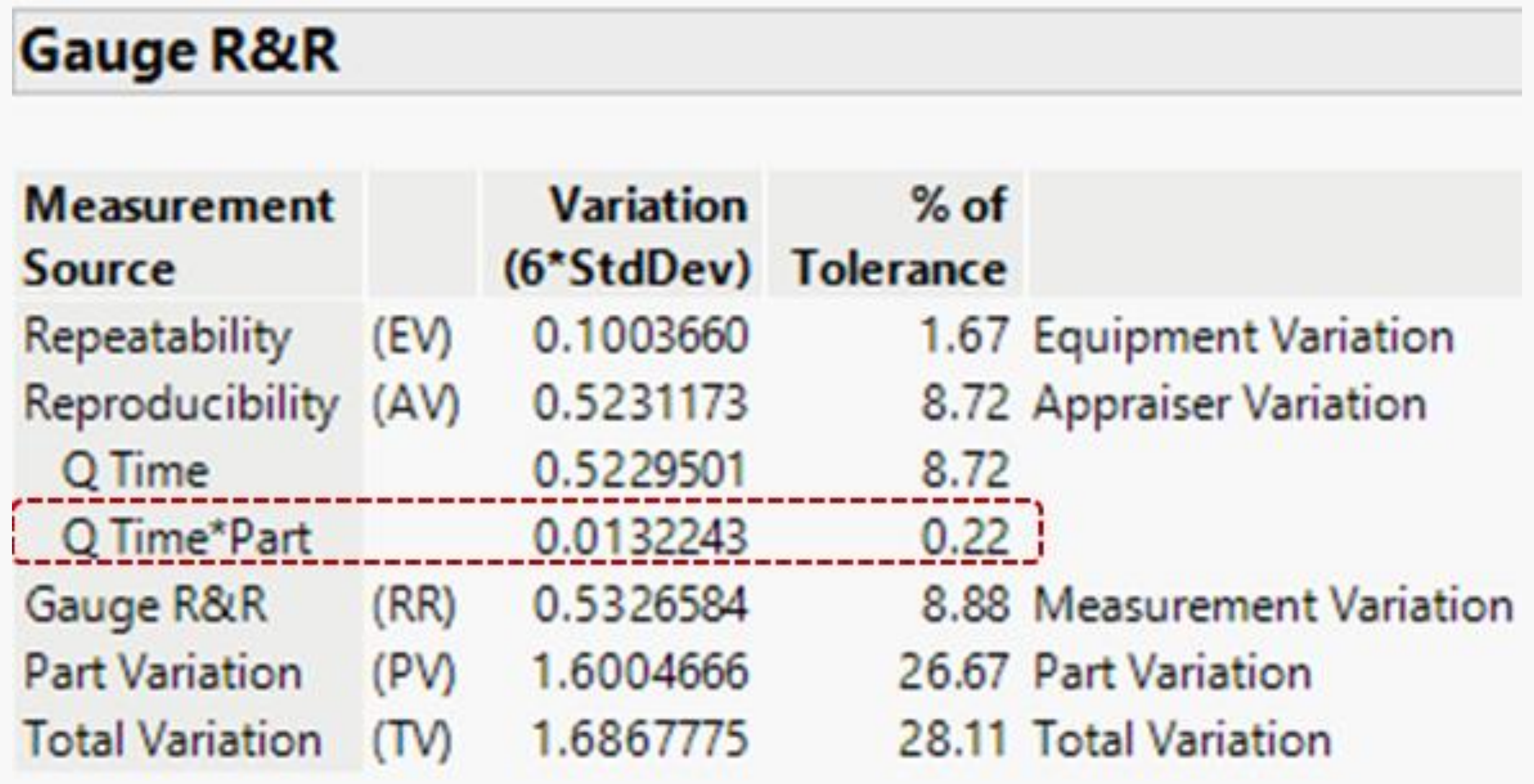
Gauge R&R

Measurement Source		Variation (6*StdDev)	% of Tolerance	
Repeatability	(EV)	0.1009628	1.68	Equipment Variation
Reproducibility	(AV)	0.5229593	8.72	Appraiser Variation
Q Time		0.5229593	8.72	
Gauge R&R	(RR)	0.5326161	8.88	Measurement Variation
Part Variation	(PV)	1.6004816	26.67	Part Variation
Total Variation	(TV)	1.6867784	28.11	Total Variation

Summary and Gauge R&R Statistics

6 k
31.5759 % Gauge R&R = 100*(RR/TV)
0.33278 Precision to Part Variation = RR/PV
4 Number of Distinct Categories = Floor(sqrt(2)*(PV/RR))
97 Lower Tolerance (LT)
103 Upper Tolerance (UT)
6 Tolerance = UT-LT
0.08877 Precision/Tolerance Ratio = RR/(UT-LT)

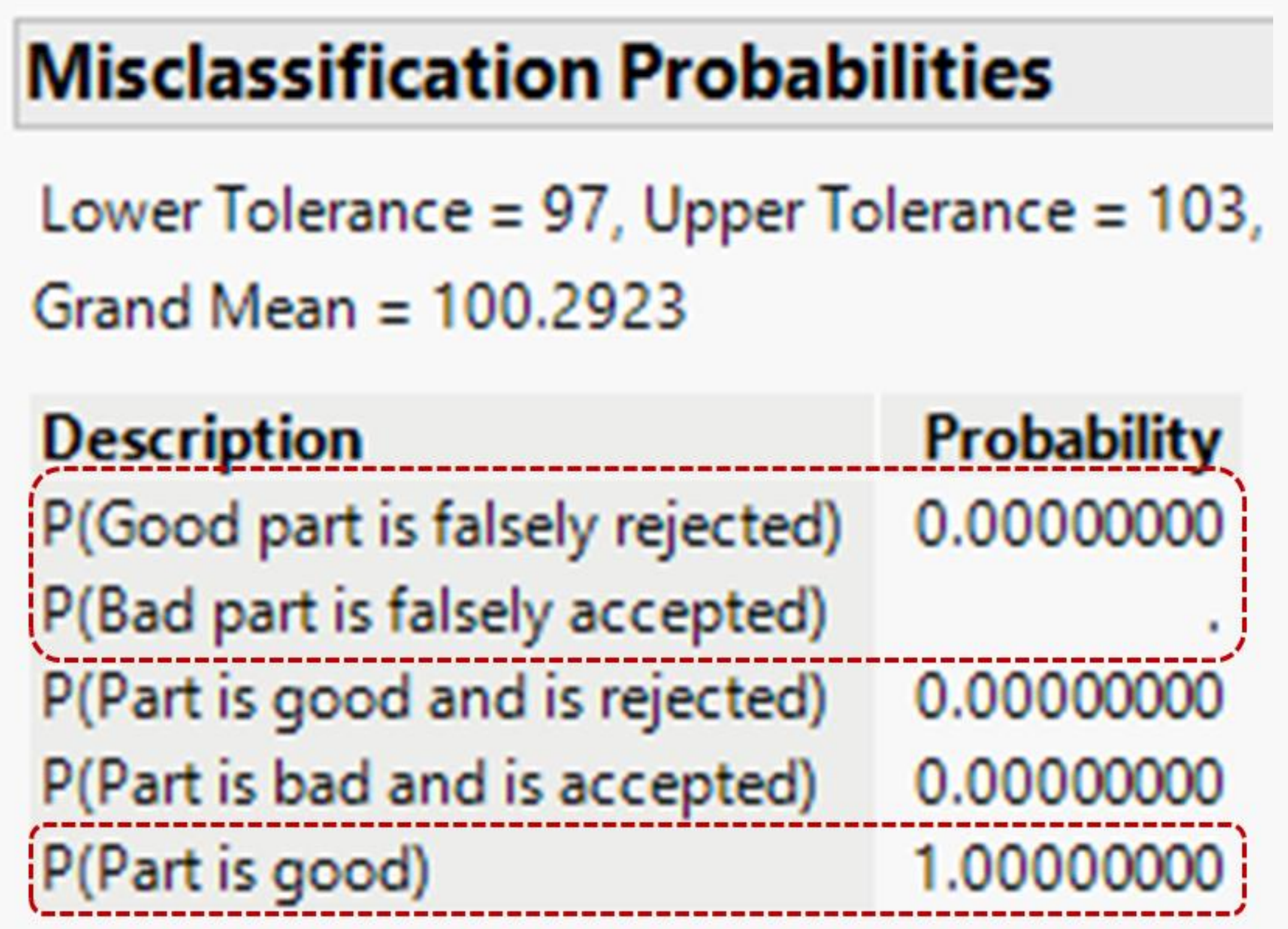
3.2 Crossed GRR (with interaction)



Gauge R&R

Measurement Source		Variation (6*StdDev)	% of Tolerance	
Repeatability	(EV)	0.1003660	1.67	Equipment Variation
Reproducibility	(AV)	0.5231173	8.72	Appraiser Variation
Q Time		0.5229501	8.72	
Q Time*Part		0.0132243	0.22	
Gauge R&R	(RR)	0.5326584	8.88	Measurement Variation
Part Variation	(PV)	1.6004666	26.67	Part Variation
Total Variation	(TV)	1.6867775	28.11	Total Variation

3.3 Misclassification Risks



Misclassification Probabilities

Lower Tolerance = 97, Upper Tolerance = 103,
Grand Mean = 100.2923

Description	Probability
P(Good part is falsely rejected)	0.00000000
P(Bad part is falsely accepted)	.
P(Part is good and is rejected)	0.00000000
P(Part is bad and is accepted)	0.00000000
P(Part is good)	1.00000000

P/TV = 31.58%

Tolerance = 6

P/T = 8.88%

» Queue Time * Part **Interaction Variation < 1%**

» **P/T ratio is preferred** to evaluate the GRR performance on tolerance

- **P/T ratio < 10%**: adequate GRR measurement capability
- **P/TV ratio > 30%**: selected GRR samples are too tight

» **All Misclassification rates: 0%**

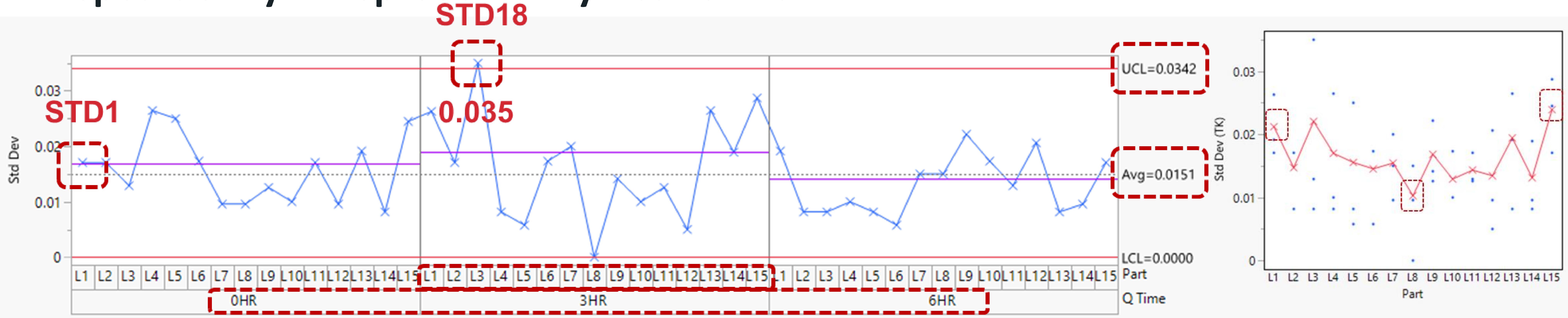
» **Calculated Alpha and Beta risks are not reliable, why?**

- **Parts are all good: 100% (all 15 parts measured in 99.6-100.6)**

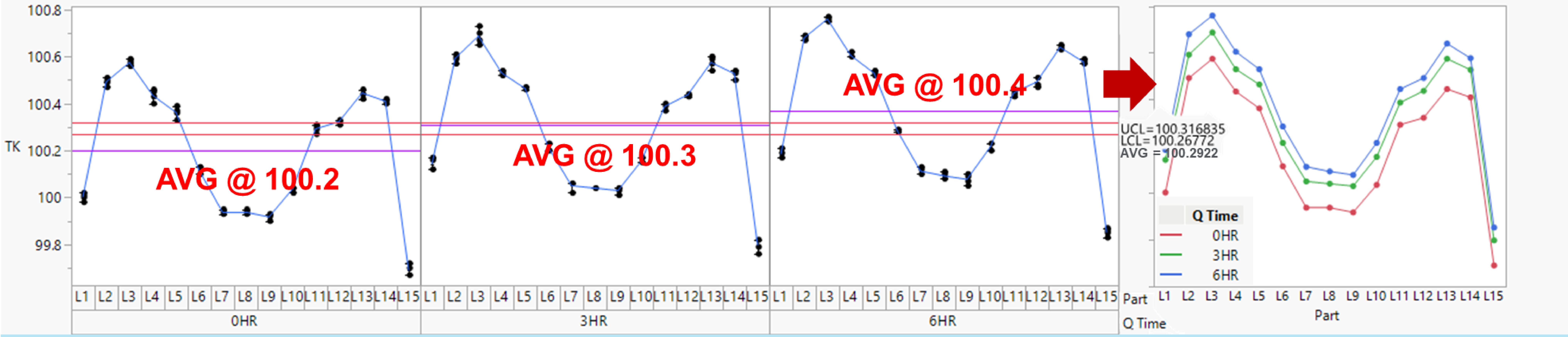
Location	Spec Limit	Control Limit	Target	Alpha Risk	Beta Risk
A	Way bwyond Spec Range	Way bwyond Control Range	Far Away from the Target	Zero	Very Low
B	Slightly outside Spec Range	Way beyond Control Range	Far Away from the Target	Low	High
C	Inside the Spec Range	Slightly outside the Control Range	Still away from the Target	High	Low
D	Inside the Spec Range	Inside the Control Range	near the Target	Low	Very Low
E	Inside the Spec Range	Inside the Control Range	At the Target	Zero	Zero

GRR Performance Root Cause Analysis

1. Repeatability & Reproducibility Xbar-S Chart

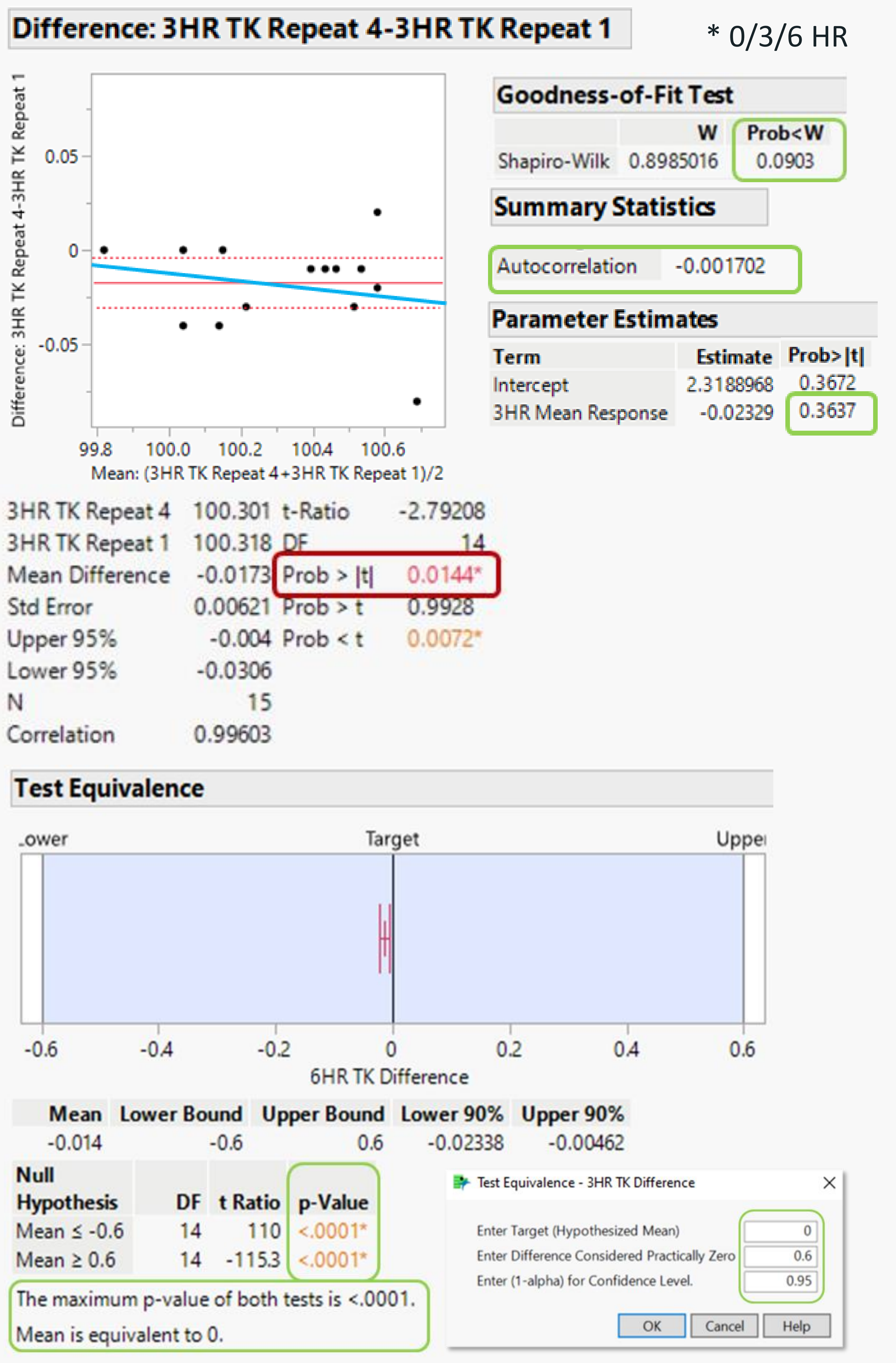


- » **Measurement is stable** within Stdev. Control Limits with **one OOC point only** (Part #3 at 3 Hours)
- » GRR Stdev by Part Plot: < 3%, weak special variation (GRR Repeatability)
  - L1&15: high STD; L8: lower STD. **Thickness is affected more at wafer edge due to internal stress**



- » The metrology tool is adequate to detect the part-part variation across three Queue Time levels **(> 50% points are beyond the control limits)**
- » Group Mean of Thickness by Queue Time (blank tests needed)
  - Thickness AVG **increases** by 0.2Å as Queue time increases from 0 to 6HR and **long-term GRR reproducibility degradation risk is very low**
- » Group Pattern of Thickness by Queue Time
  - **Three curves are parallel in Queue time (Reproducibility)** and little Part*Queue Time interaction is observed

2. Short-term Degradation Risk



Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8985016	0.0903

Summary Statistics

Autocorrelation	-0.001702

Parameter Estimates

Term	Estimate	Prob>|t|
Intercept	2.3188968	0.3672
3HR Mean Response	-0.02329	0.3637

3HR TK Repeat 4	100.301	t-Ratio	-2.79208
3HR TK Repeat 1	100.318	DF	14
Mean Difference	-0.0173	Prob > |t|	0.0144*
Std Error	0.00621	Prob > t	0.9928
Upper 95%	-0.004	Prob < t	0.0072*
Lower 95%	-0.0306		
N	15		
Correlation	0.99603		

Test Equivalence

Mean	Lower Bound	Upper Bound	Lower 90%	Upper 90%
-0.014	-0.6	0.6	-0.02338	-0.00462

Null Hypothesis	DF	t Ratio	p-Value
Mean ≤ -0.6	14	110	<.0001*
Mean ≥ 0.6	14	-115.3	<.0001*

The maximum p-value of both tests is <.0001.

Mean is equivalent to 0.

Enter Target (Hypothesized Mean): 0
Enter Difference Considered Practically Zero: 0.6
Enter (1-alpha) for Confidence Level.: 0.95

- » Degradation is insignificant compared to spec

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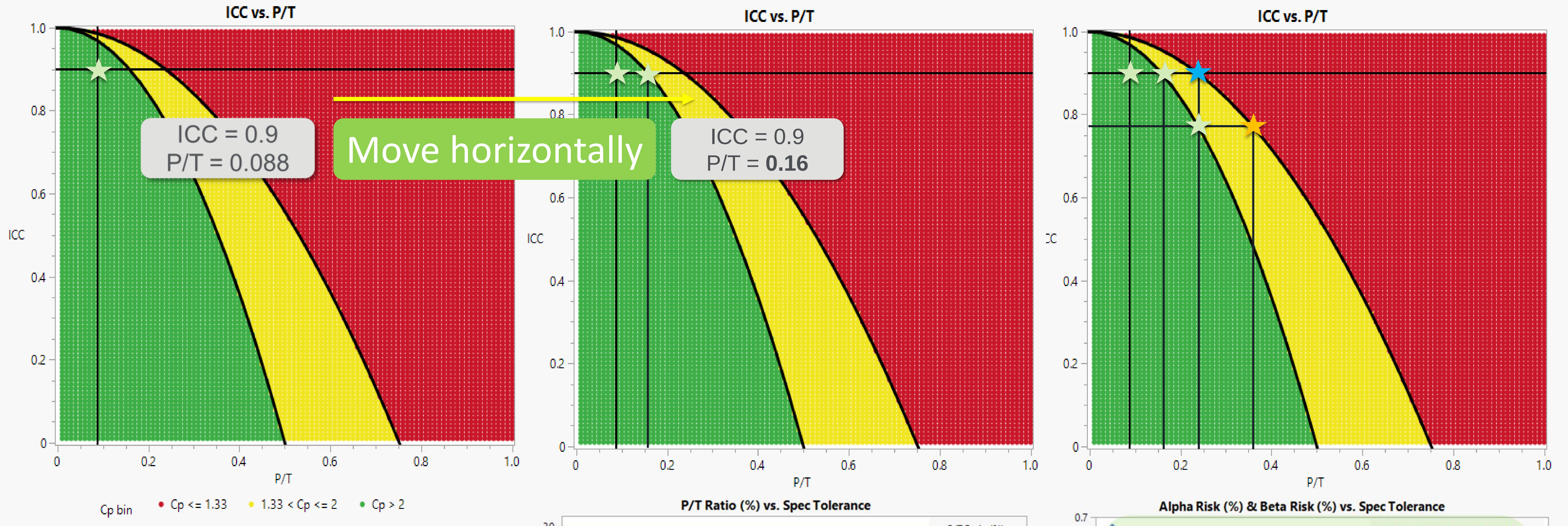
EMP/ICC, P/T and Process Capability

1. EMP ICC and P/T Plot

EMP Test	Results
Test-Retest Error	0.0168
Degrees of Freedom	163
Probable Error	0.0113
Intraclass Correlation (no bias)	0.996
Intraclass Correlation (with bias)	0.9003

$$ICC = \frac{\sigma^2_{part}}{\sigma^2_{part} + \sigma^2_{gauge}} \qquad P/T = \frac{6\hat{\sigma}_{gauge}}{USL - LSL} \qquad C_p = \frac{\sqrt{1 - ICC}}{P/T}$$



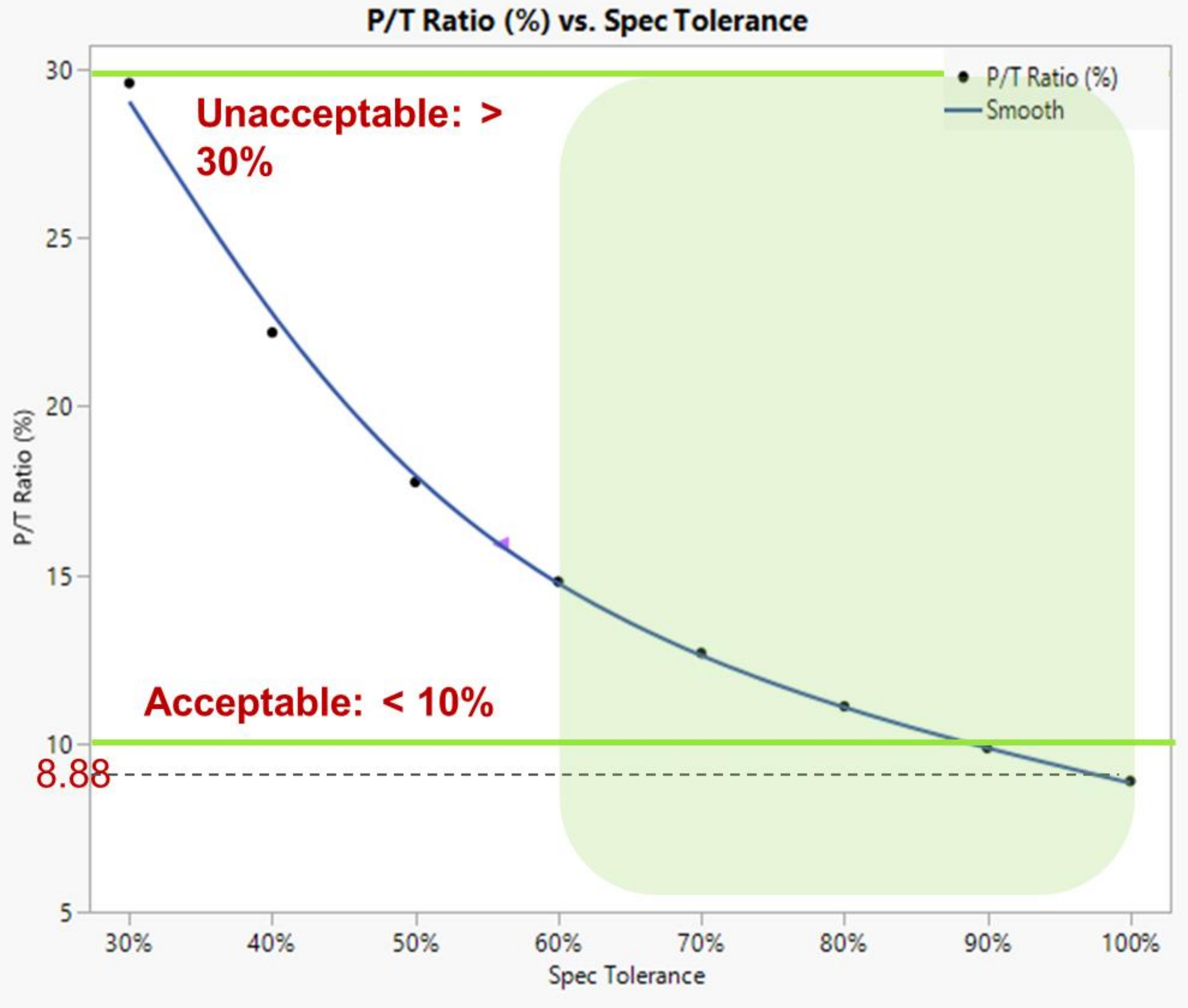
ICC = 0.9
P/T = 0.088

Move horizontally

ICC = 0.9
P/T = **0.16**

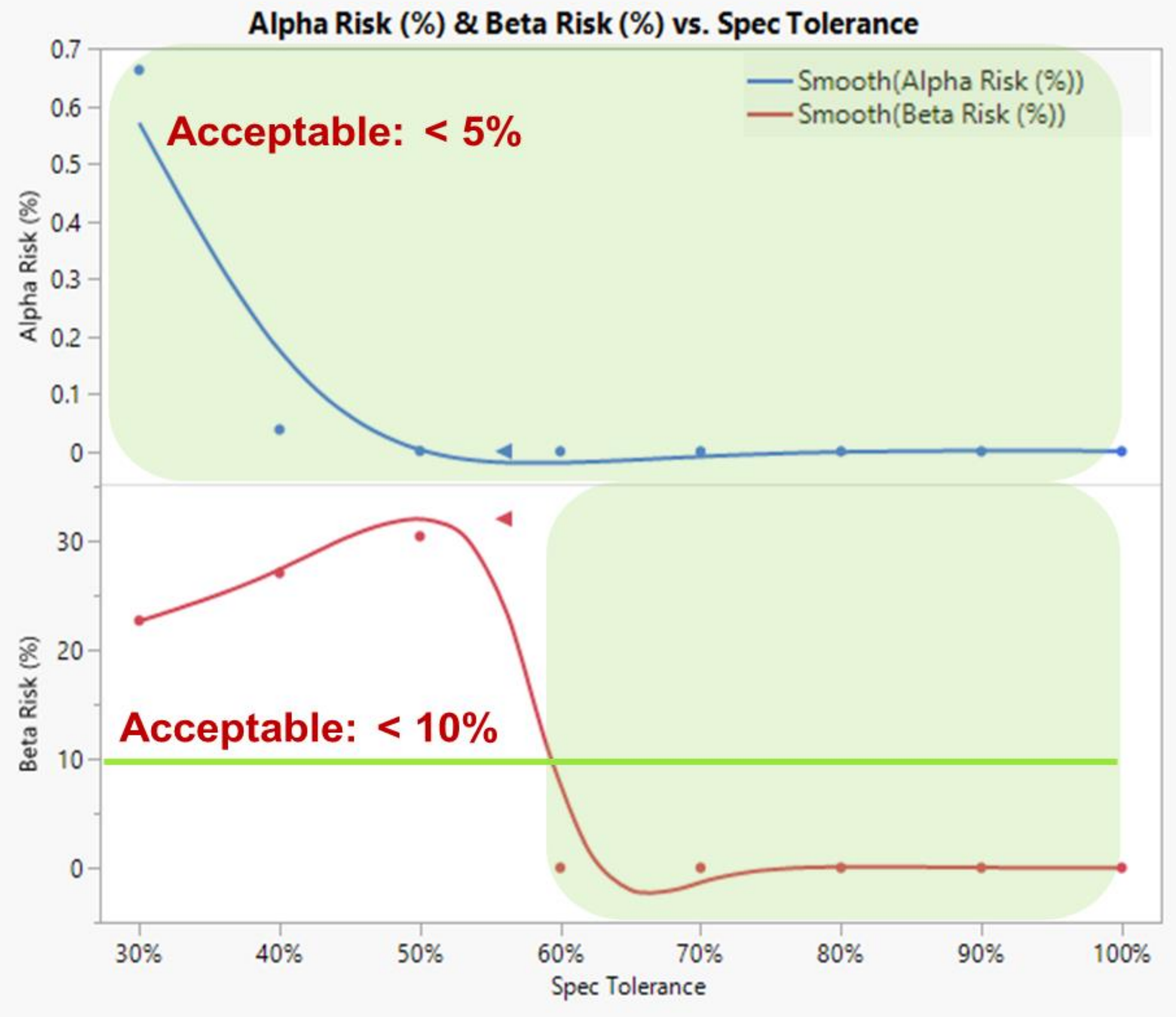
Based on what tolerance will process become less capable?

What about the P/T ratio, alpha and beta risks with tightening spec?



Unacceptable: > 30%

Acceptable: < 10%



Acceptable: < 5%

Acceptable: < 10%

2. Continuously improve GRR and PpK

★ **When Cp >= 2, P/T < 0.3**

=> Tighten Spec until Cp=1.33

★ **When Cp <= 1.33, P/T < 0.3**

=> Improve Process Part-Part Capability (Reduce ICC) until Cp = 2

★ **When Cp <= 1.33, P/T > 0.3**

=> Improve GRR < 0.3 (also improve Cp)

Iteratively and continuously improve the Process Capability and Measurement Capability