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Role of Process Control in Improving Space Vehicle Safety
A Space Shuttle External Tank Example

Fayssal M. Safie, Ph. D.
Marshall Space Flight Center
Huntsville, Alabama

Son C. Nguyen
Lockheed Martin Michoud Space Systems
New Orleans, Louisiana

Keith W. Burleson
Marshall Space Flight Center
Huntsville, Alabama

Abstract

Developing a safe and reliable space vehicle requires good design and good manufacturing, or in other words "design it right and build it right". A great design can be hard to build or manufacture mainly due to difficulties related to quality. Specifically, process control can be a challenge. As a result, the system suffers from low quality which leads to low reliability and high system risk. The Space Shuttle has experienced some of those cases, but has overcome these difficulties through extensive redesign efforts and process enhancements. One example is the design of the hot gas temperature sensor on the Space Shuttle Main Engine (SSME), which resulted in failure of the sensor in flight and led to a redesign of the sensor. The most recent example is the Space Shuttle External Tank (ET) Thermal Protection System (TPS) reliability issues that contributed to the Columbia accident. As a result, extensive redesign and process enhancement activities have been performed over the last two years to minimize the sensitivities and difficulties of the manual TPS application process.

This paper discusses the importance of quality in system design, and the

relationship between quality, reliability, and system safety for space vehicles. It uses examples from the Space Shuttle System with an emphasis on the ET TPS experience. It also discusses the redesign and process enhancement activities and shows how process control has improved TPS reliability and overall safety of the Space Shuttle vehicle in preparation for Return to Flight.

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Safie, Fayssal M. Ph.D[(1)], Nguyen, Son C.[(2)]

[(1)] NASA/MSFC, Huntsville Al 35812, fayssal.m.safie@nasa.gov:
[(2)] Lockheed Martin/MSS, 13800 Old Gentilly Rd New Orleans La 70129, son.c.nguyen@maf.nasa.gov:

ABSTRACT

Developing a safe and reliable space vehicle requires good design and good manufacturing, or in other words “design it right and build it right”. A great design can be hard to build or manufacture mainly due to difficulties related to quality. Specifically, process control can be a challenge. As a result, the system suffers from low quality which leads to low reliability and high system risk. The Space Shuttle has experienced some of those cases, but has overcome these difficulties through extensive redesign efforts and process enhancements. The most recent example is the Space Shuttle External Tank (ET) Thermal Protection System (TPS) reliability issues that contributed to the Columbia accident. As a result, extensive redesign and process enhancement activities have been performed over the last two years to minimize the sensitivities and difficulties of the manual TPS application process.

This paper discusses the importance of quality in system design, and the relationship between quality, reliability, and system safety for space.

1.0 BACKGROUND

In the past, space vehicle designers focused more on performance and less on other system parameters.

Reliability and safety was covered by designing for high safety factors. Safety factors are good if processes are in control and engineering analyses are bounding. However, past experience has shown that even for the best design, engineering analyses are not bounding in cases of excessive process variability and lack of process control.

Developing a safe and reliable space vehicle requires good design and good manufacturing, or in other words “design it right and build it right”. Inadequate process control could result in low quality which leads to low reliability and high system risk.

The difficulties and sensitivities of the Space Shuttle External Tank (ET) Thermal Protection System (TPS) manual spray process is a good demonstration of the impact of process control on component reliability and system risk. The TPS is a foam type material applied to the ET to maintain cryogenic propellant quality, minimize ice/frost formation, and protect the structure from ascent, plume, and re-entry heating.

The ET main TPS components are shown in Fig. 1. ET main TPS components are applied by automated and/or manual processes.

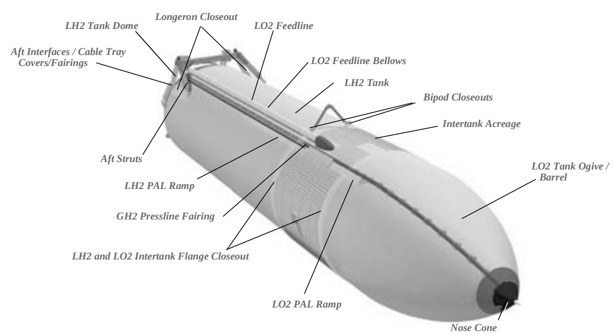

Fig. 1. ET Main Thermal Protection System

As a result of the Columbia accident, some manually applied components of the TPS were enhanced/redesigned to reduce defects. A type of defect of main concern, which was the focus of the RTF activities, was the presence of voids within the TPS foam. Fig. 2 shows the enhanced/redesigned manually applied TPS components.

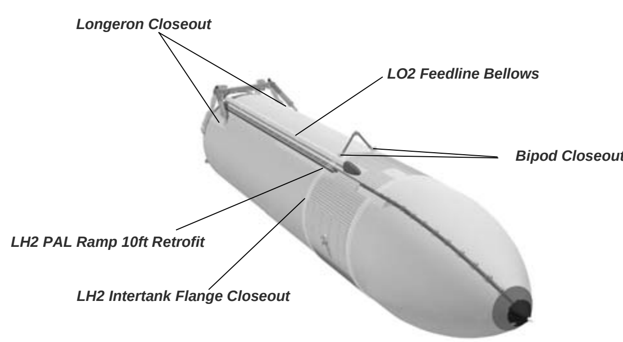

Fig. 2. Enhanced/Redesigned ET Parts

2.0 ET RETURN TO FLIGHT (RTF) LESSONS LEARNED

The following sections discuss the lessons learned from ET return to flight (RTF) with regard to process control and its impact on TPS reliability and Space Shuttle risk. Section 2.1 addresses the relationship between process control, reliability and system risk. The rest of the sections address specific experiences from ET RTF.

2.1 RELATIONSHIP BETWEEN PROCESS CONTROL, RELIABILITY, AND SYSTEM RISK

Quality engineering, and more specifically process control, is the most important factor in reducing the Space Shuttle system risk. Good process control for ET TPS translate to lower number and smaller foam defect sizes in the TPS foam or more material capability. Lower defect numbers and smaller foam defect sizes translate to lower divot numbers and smaller divot sizes released in flight that could hit the Orbiter and cause a Space Shuttle catastrophic failure. In other words, higher TPS material capability means better TPS reliability and lower Shuttle risk. Fig. 3 shows the relationship between quality, reliability, and system risk. The following paragraphs discuss this relationship as applied to ET TPS foam.

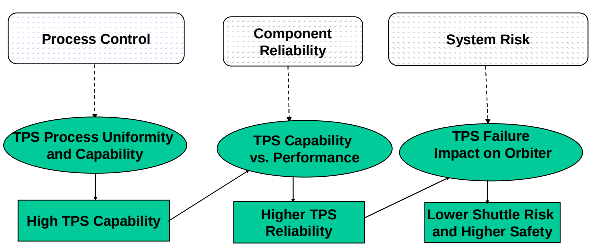

Fig. 3. Relationship between Process Control, Reliability, and System Risk

We more often talk about process control in terms of Statistical Process Control (SPC). The scope of process control is much broader than SPC. Fig. 4 depicts the major elements of ET TPS process control or integrated process control (IPC). As shown in the figure, ET TPS IPC involved SPC, TPS application process control, manufacturing material control, contamination control, supplier process control, process change verification control, process monitoring, training and operator certification, and configuration management control.

IPC was critical in ensuring consistent processes were employed for every part of the ET TPS. The focus of the ET project has been on SPC, standardization of spray techniques, early detection of changes in materials, comprehensive technician, operator and QC training, video review, process parameter data recording, and Quality Control (QC) inspection. The ET TPS SPC activity involved identification of process factors that affect the product quality, determination of the relative magnitude of the factors and the factors' numerical sensitivity, and monitoring of the process critical factors.

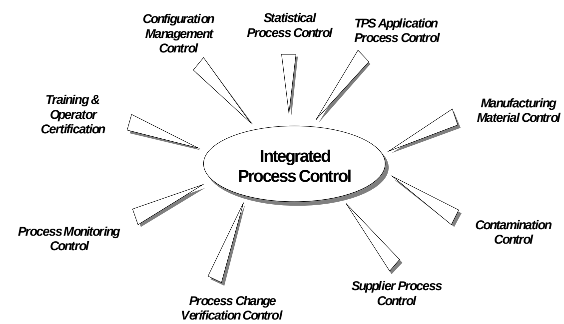

Fig. 4. ET TPS Integrated Process Control

The output of ET process control has been the most critical input to TPS reliability. As shown in Fig. 5, TPS reliability is defined in terms of TPS capability and system operating environment. TPS capability is defined in terms of material properties, process uniformity, and process capability. Process uniformity and process capability are characteristic of process defect frequency and size. For a manually sprayed TPS, the process uniformity and process capability are mainly driven by process control. In other words, ET TPS reliability is mainly driven by TPS process control.

The output of TPS reliability is a set of probability distributions of TPS divot frequencies and divot sizes which are derived from the process defects when these defects are subjected to the flight operating environment. The TPS reliability output is a critical input to the Shuttle system risk assessment.

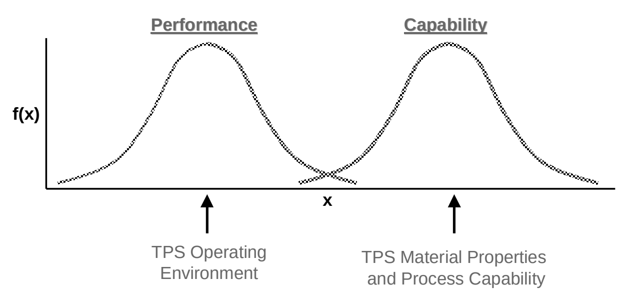

Fig. 5. TPS Reliability

TPS failure impact on Shuttle risk was evaluated using a probabilistic physics based engineering approach [1] [2]. Traditional Probabilistic Risk Assessment (PRA) involves all the scenarios that impact system risk [3].

The output of a PRA is an uncertainty distribution on system risk. The TPS probabilistic physics based engineering risk assessment focused on the impact of a failure mode on the system risk. The output was a point estimate of the risk. Confidence was heavily dependent on the level of conservatism of the engineering data and engineering assumptions.

Sections 2.2 and 2.3 address the characterization and evaluation for both redesigned/enhanced and non redesigned (Use-As-Is) TPS. Section 2.4 describes the process that the Shuttle program and ET project used to assess the TPS reliability and system risk using the information and data characterization generated by the effort described in sections 2.2 and 2.3.

2.2 Evaluation and Characterization of Redesigned ET TPS

The following section discusses the approach used for improvements and evaluations related to manually applied TPS components.

Manually applied ET TPS components were improved in two different aspects; a redesign of the TPS component, and an enhancement of the manual TPS application process specific to that component.

ET TPS component redesign addresses the relationship between substrate geometry and defect formation. For example, the complexity of the underlying substrate was reduced, which corresponds to a reduction in the number and size of defects induced by complex substrates.

Enhancement of the manual TPS application process included considerations for reduced operator to operator variability. For example, the sequence of operations were better organized and well defined with emphasis on operator training and certification specific to an ET TPS component. This allowed for a more consistent application process.

Verification and validation testing of each TPS component redesign was performed, which provided sufficient data to evaluate and characterize the process variability and process capability. Process readiness was also evaluated using pre-control charts [4].

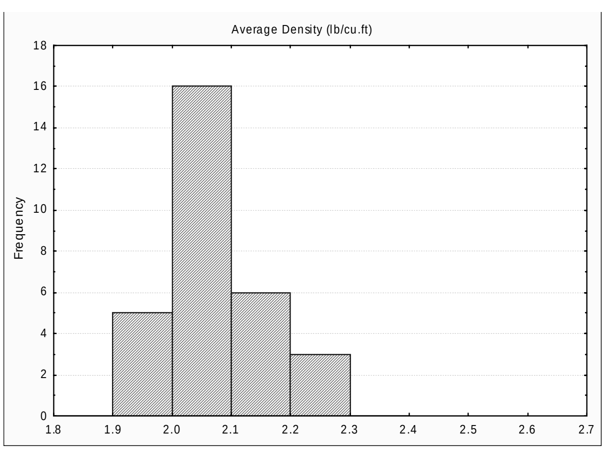

Fig. 6. Example: Bipod Final Closeout Average Density

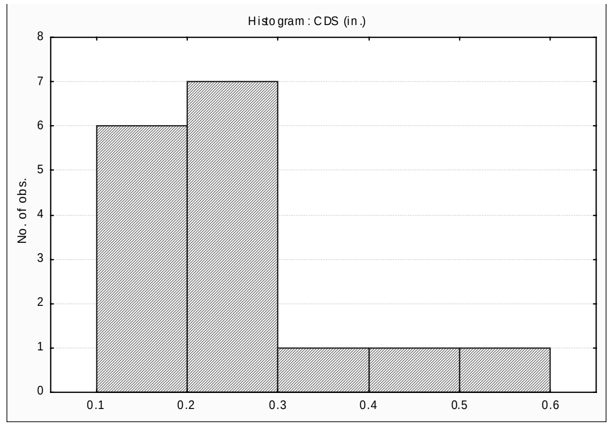

Fig. 7. Example: Bipod Closeout Slot Void Sizes

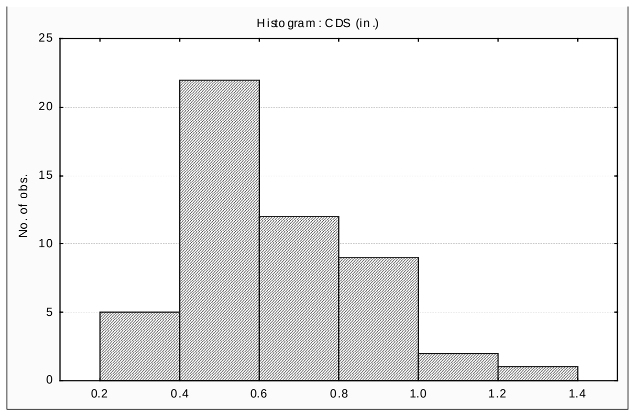

Fig. 8. Example: Bipod Closeout Cylinder Void Sizes

Statistical evaluation of the data showed that significant improvements were made in process uniformity and process capability for material properties for the enhanced/redesigned ET TPS components. Significant reduction was detected in the coefficient of variation (COV) of the process critical output parameters (e.g. density, plug pull, voids, etc.). Fig. 6 shows an example of the Bipod Closeout redesign average density distribution. Furthermore, there was a significant reduction in the frequency and size of defects for the enhanced/redesigned ET TPS components. However, void characterization was still difficult because of limitation of the data and lack of good definition of the right tail of the data distribution [5]. Fig. 7, and Fig. 8, shows examples of the defect size distribution for the Bipod Closeout.

For certification, a max expected void size was derived based on statistics and engineering analysis of the redesigned ET TPS component and then compared to an engineering limit derived from test data.

2.3 Evaluation and Characterization of Use-As-Is TPS

The following section discusses the evaluation of Use-As-Is TPS components.

Process variability for Use-As-Is Foam was evaluated after the fact, without complete information about process variation and controls. For example, the natural variation of the process was not well understood, and the relationship between process control variables and defects was not known.

The dissection data collected after the Columbia accident showed excessive variability (Coefficient of variation is greater than 100%) for process defect sizes and frequency. Within tank defect variability was high, and tank to tank defect variability could not be fully characterized due to limited data. Defect/void characterization was difficult and statistics derived had a high level of uncertainty. There was also a lack of random samples of sufficient size to empirically select a distribution for characterization. Furthermore, there was no engineering rationale to pick a specific distribution. Finally, there were very limited data to characterize the right tail of the distribution [6].

As a result of the above process control unknowns and data limitations, statistics was used only as supporting data for engineering evaluation and analysis. Additionally, engineering factors were used in the derivation of certification limits as a penalty to compensate for the lack of complete understanding of process controls and the statistical limitations of the data.

2.4 Shuttle ET TPS Risk Assessment

As mentioned earlier in the paper, the impact of TPS failure on Shuttle risk was evaluated using a physics based probabilistic engineering simulation approach. As shown in Fig. 9, the main input to the simulation model was the ET TPS void distributions derived from the dissection data of the ET components under consideration. The void distributions were then used in a fracture mechanics model to generate divots. The divots generated were then transported to evaluate the damage impact on the orbiter. The output of the model was the probability of Orbiter damage exceeding a specified tolerance limit set for the Orbiter. It is important to note that the void distributions, which included both the sizes of voids and the frequency of voids, represented the output of the ET TPS manual process which is basically driven by process control.

The risk assessment model, although limited in scope, was very critical in understanding and communicating the risk of the ET TPS in flight.

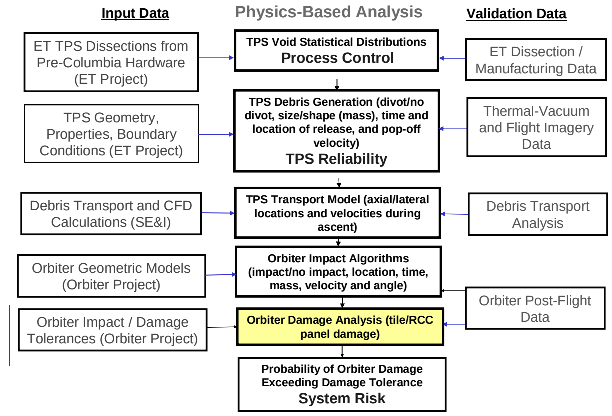

Fig. 9. Shuttle ET TPS Risk Assessment Approach

3.0 CONCLUSION

Lessons learned from ET RTF experience demonstrates that a minor problem in process control could lead to a major problem at the system level which could significantly impact system risk. Consequently, good process control is essential in achieving high component reliability and low system risk. Manufacturing and process control should be considered up front in the design phase. Component designers of future launch vehicles should, consider manufacturability as well as the feasibility of good process control in the design selection process. To ensure consideration of process control throughout the program, an integrated process control plan should be developed upfront, and implemented throughout the different phases of the program.

4.0 REFERENCES

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Mission Success Starts with Safety

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Agenda

- **Background**
- **Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned**
  - **Relationship Between process Control, Reliability, and System Risk**
  - **Evaluation and characterization of redesigned components and process enhanced foam**
  - **Evaluation and characterization of Use-as-is foam**
  - **Risk assessment using probabilistic engineering approach**
- **Conclusions**

Background

- In the past, space vehicle designers focused on performance and less on other system parameters
- Reliability and safety was covered by designing for high safety factors
- Safety factors are good if processes are in control and engineering analyses are bounding.
- Past experience has shown that even for the best design, engineering analyses are not bounding in cases of excessive process variability (lack of process control)

Background

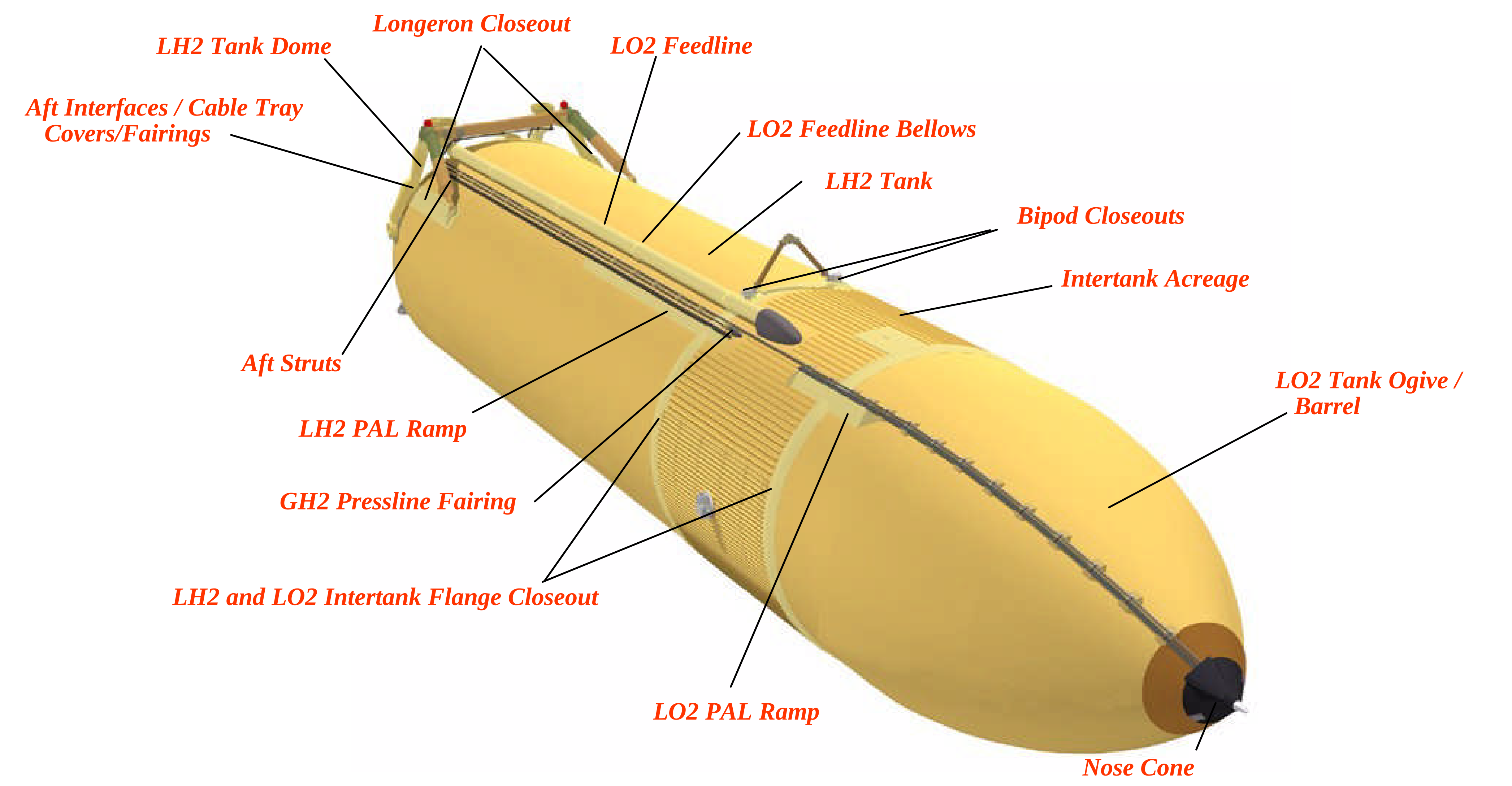
- Developing a safe and reliable space vehicle requires good design and good manufacturing, or in other words "design it right and build it right"
- Inadequate process control could result in low quality which leads to low reliability and high system risk
- The difficulties and sensitivities of the ET TPS manual spray process is a good demonstration of the impact of process control on component reliability and system risk

Background

The Shuttle External Tank (ET) Thermal Protection System (TPS)

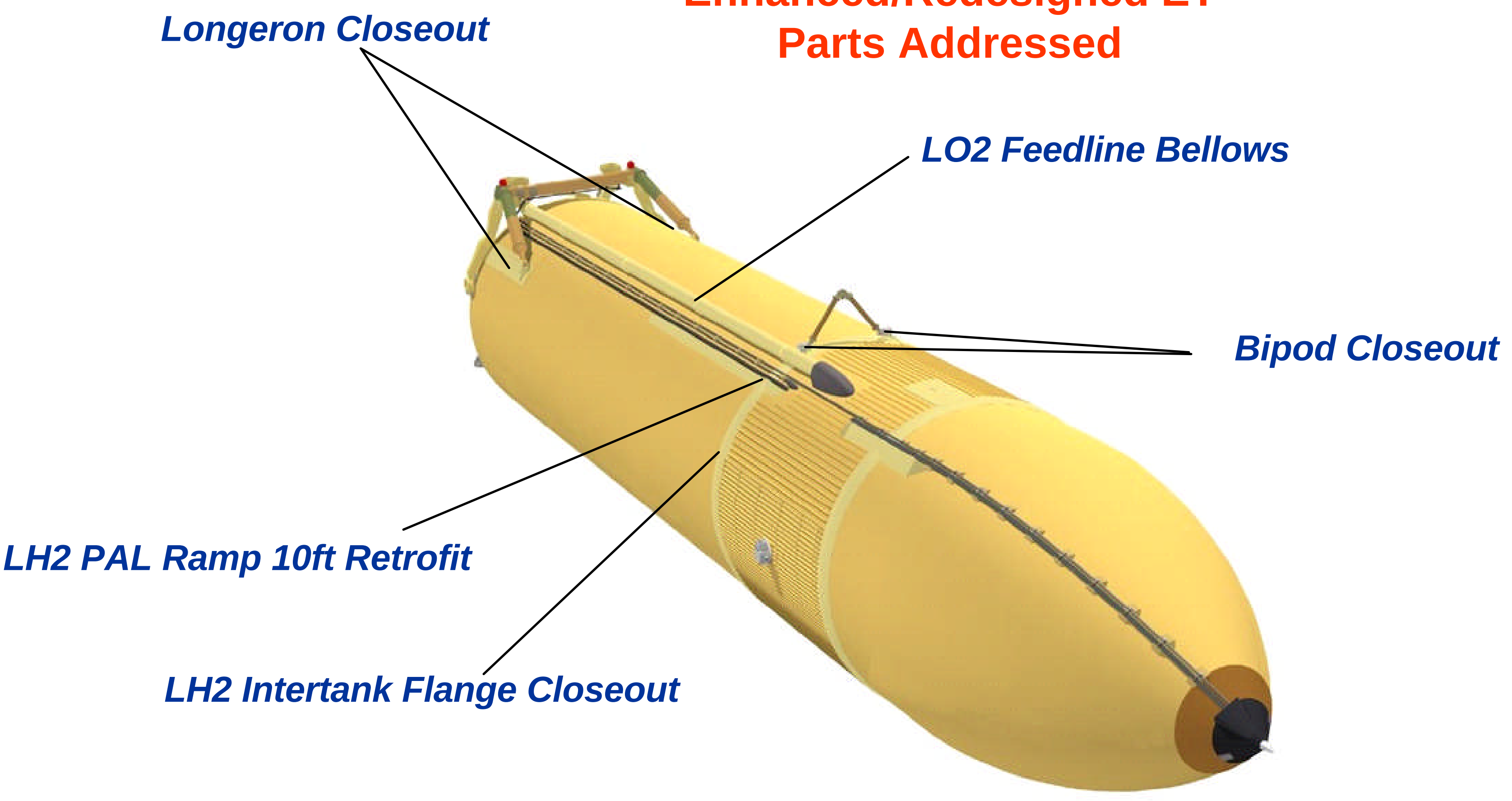
The TPS is applied to the ET to maintain cryogenic propellant quality, minimize ice/frost formation, and protect the structure from ascent, plume, and re-entry heating

Background
Thermal Protection System Overview



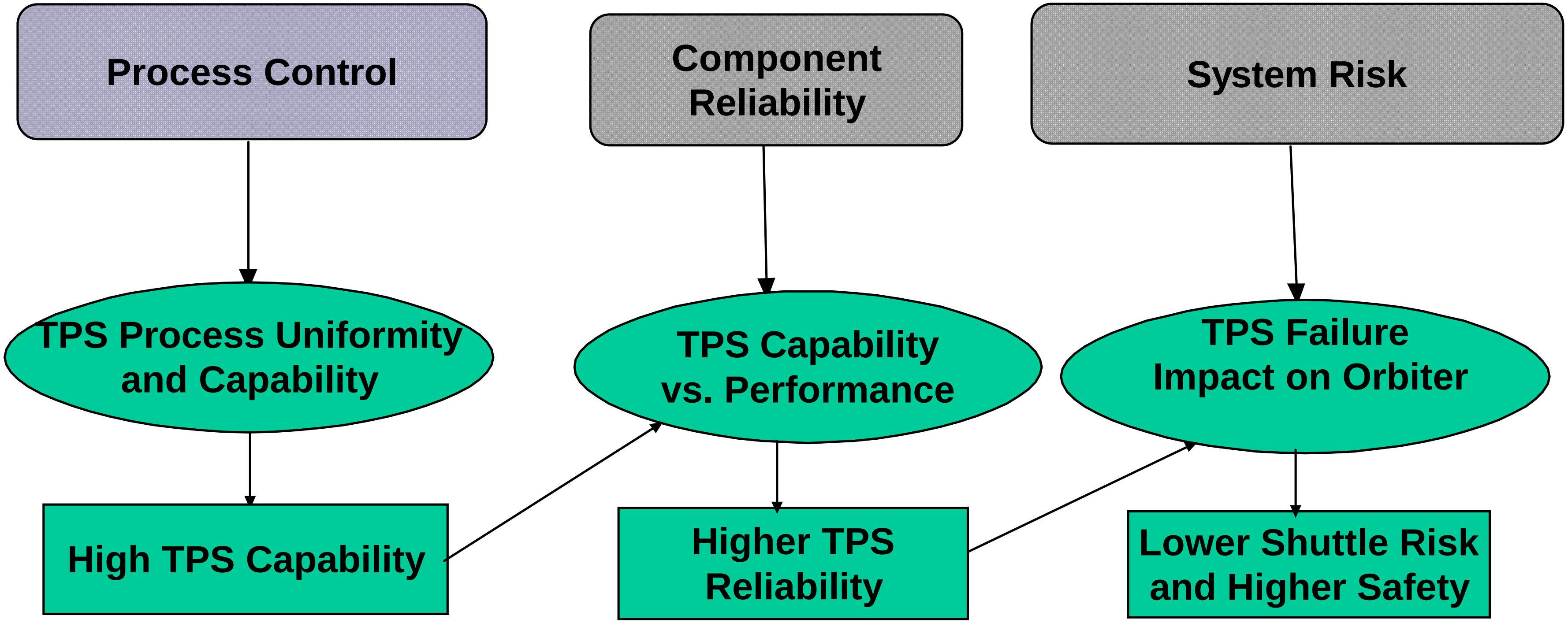
Background
Components and Process Enhanced Foam

Enhanced/Redesigned ET Parts Addressed



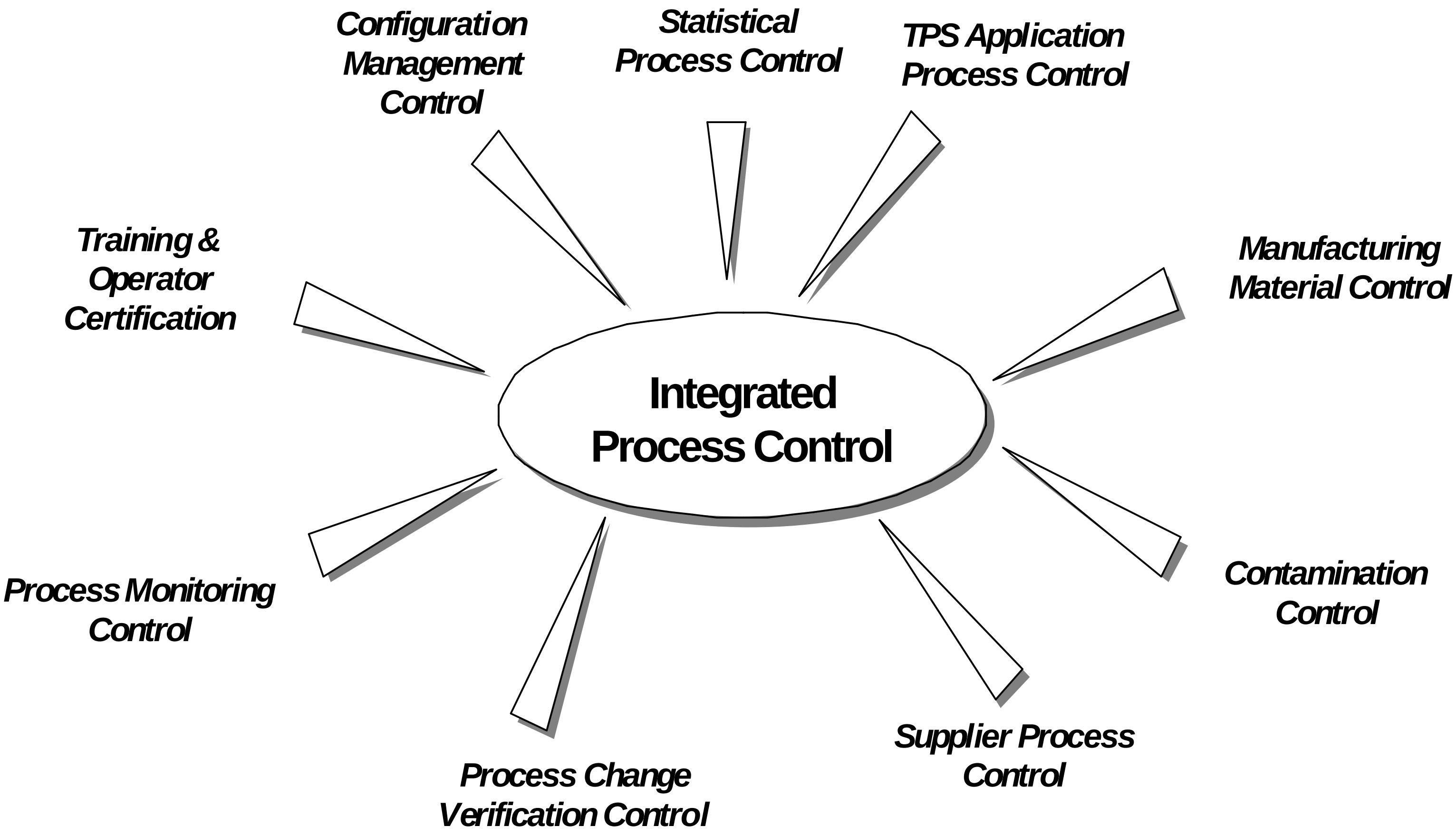
Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

Relationship Between process Control, Reliability, and System Risk



Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

ET TPS Integrated Process Control



Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

ET TPS Integrated Process Control

- Integrated process control (IPC) is critical to ensure consistent processes are employed for every part. Major activities in IPC for ET foam are:
  - Identification and control of critical processing variables
  - Standardization of spray techniques
  - Early detection of changes in materials and processes
  - Comprehensive technician, operator and QC training
  - Video review
  - Process parameter data recording
  - QC inspection

Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

Statistical Process Control

- Characterize the process to identify which process factors affect the product, the relative magnitude of the factors and the factors' numerical sensitivity.
- Determine critical process factors for process monitoring. The critical process factors and sources of variability is determined using tools such as Design of Experiments (DOE), regression analysis, etc.
- Establish requirements and guideline for detection and adjustment of out of control processes. The guidelines shall be based on process characterization and experience
- Define a sampling plan for product acceptance

- Maintain an electronic record of process performance

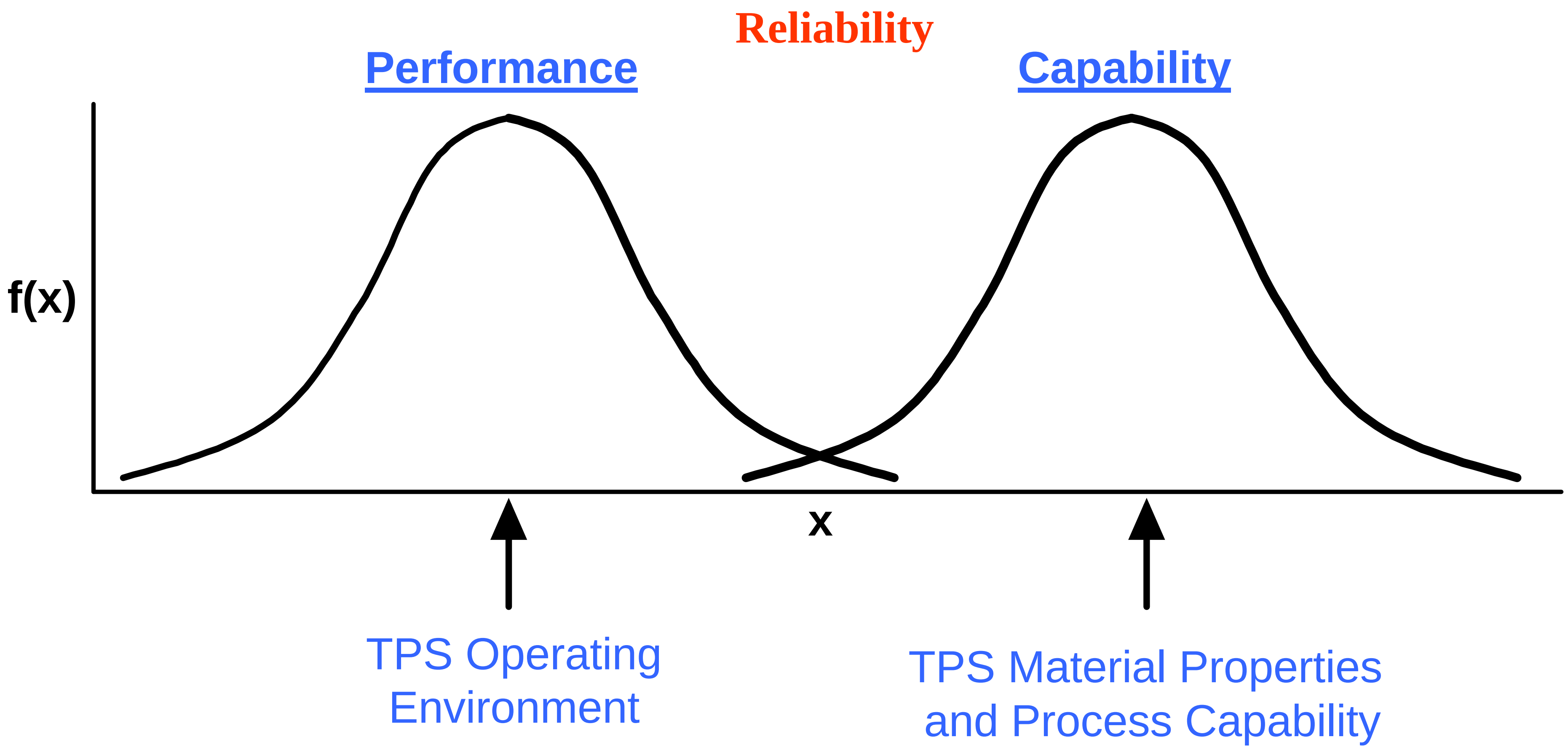
Statistical Process Control

- A quality Engineering issue
- Statistical in nature
- TPS statistical data is extensive
- The output of process control is a uniform and capable process
- A critical input to the TPS reliability

Reliability

- Probabilistic in nature
- It deals with capability (material properties and process capability) versus performance (system operating environment)
- The output is a probability distribution
- It is a critical input to the probabilistic system engineering and system risk assessment

Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

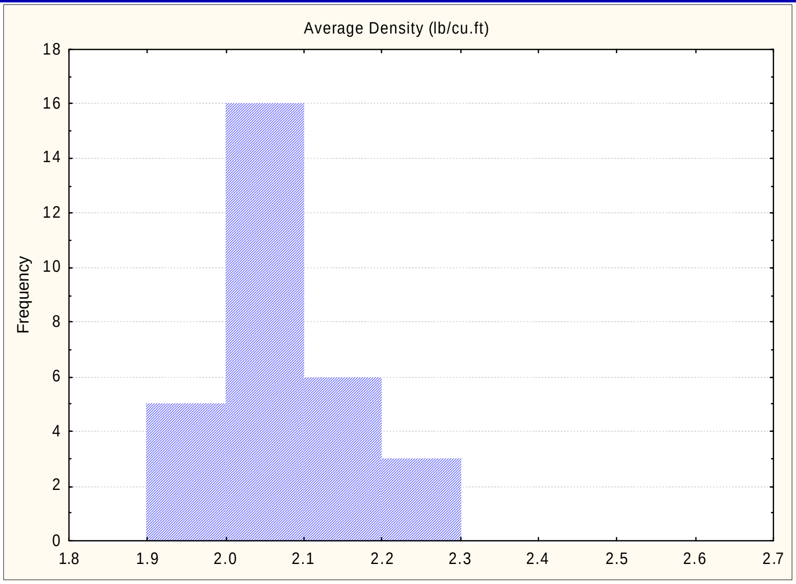


Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

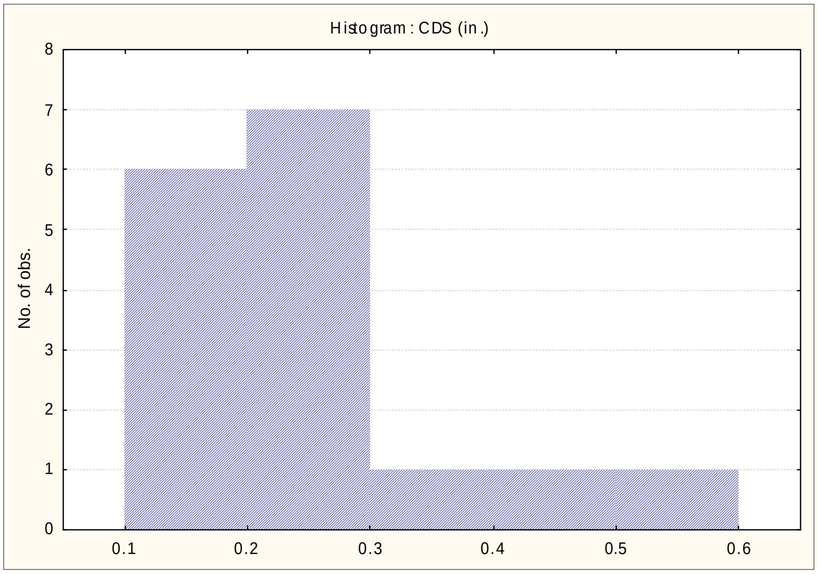
Evaluation and characterization of redesigned components and process enhanced foam

- **Approach for redesigned components and process enhanced foam**
  - Improve process/design
  - Conduct verification and validation testing sufficient enough to understand and characterize the process variability and process capability
  - Evaluate process pre-control charts for process readiness
  - Evaluate process capability for meeting the specification
  - Evaluate process control for process uniformity
  - Statistically characterize process output for certification

Example
Bipod Final Close Out Average Density

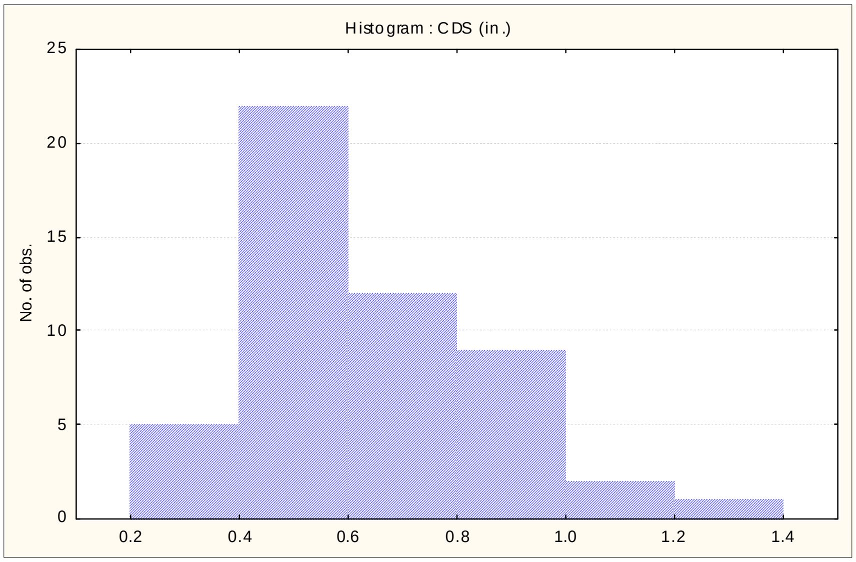


Example
Bipod Closeout Slot Voids



Void Size (in)

Example
Bipod Closeout Cylinder Voids



Void Size (in)

Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

Evaluation and characterization of redesigned components and process enhanced foam

- **Statistical evaluation of the data for the enhanced/redesigned ET TPS showed:**
  - Significant improvement in process uniformity and process capability for material properties
  - Significant reduction in frequency and size of defects
  - Significant reduction in the coefficient of variation (COV) of the process critical output parameters (e.g. density, plug pull, voids, etc.)
  - Better characterization of material properties.
  - Void characterization was still difficult because of limitation of the data and lack of good definition of the right tail of the data distribution
- **For Certification:**
  - A max expected void size was derived based on statistics and engineering analysis
  - The max expected void size derived was compared to an engineering limit derived from test data

Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

Evaluation and characterization of Use-as-is foam

- Process variability was evaluated after the fact
- Dissection data collected after the Columbia accident showed excessive variability (Coefficient of variation is greater than 100%)
- Within tank variability was high, and tank to tank variability could not be fully characterized
- Defect/void characterization was difficult and statistics derived had high level of uncertainty
  - There was a lack of random samples of sufficient size to empirically select a distribution
  - Very limited data to characterize the right tail of the distribution
  - There is no engineering rationale to pick a specific distribution

Shuttle External Tank (ET) Return to Flight (RTF) Lessons learned

Evaluation and characterization of Use-as-is foam

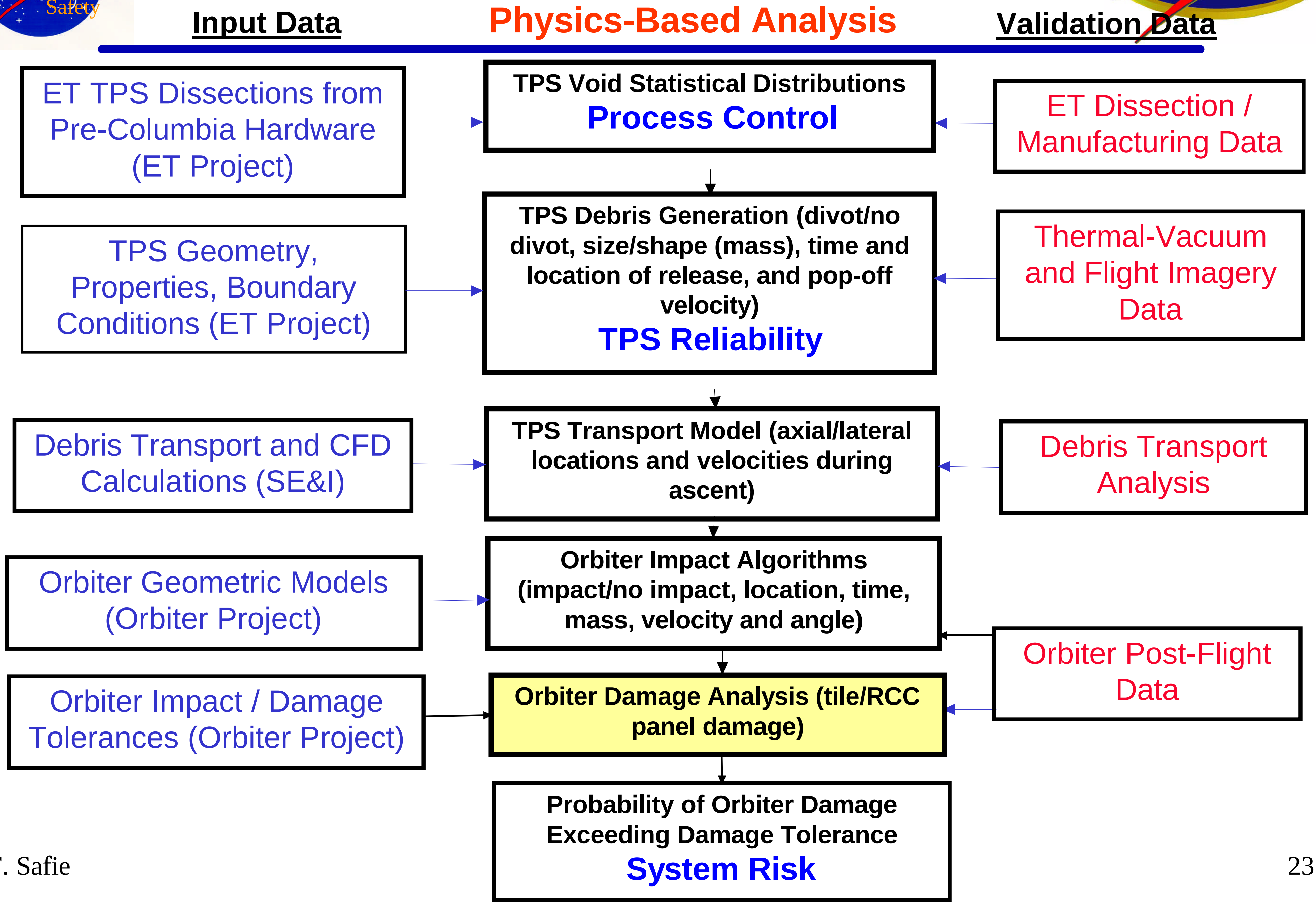
- The natural variation of the process was not well understood
- Process controls related to manually-sprayed foam were related to environmental parameters. The relationship between process control variables and defects is not known
- For certification:
  - A max expected void size was derived based on statistics and engineering analysis
  - The max expected void size derived was compared to an engineering limit derived from test data

Risk Assessment Using Probabilistic Engineering Approach

- Traditional Probabilistic Risk Assessment (PRA)
  - Involves all the scenarios (multiple events) that impact system risk
  - The output is an uncertainty (or confidence) distribution on system risk (e.g. the risk is less than 1 in 1000 with 50% confidence)

- Probabilistic Engineering Assessment focuses on the impact of a failure mode on the system risk
  - The output, in general, is a point estimate of the risk (e.g. the risk is 1 in 1000).
  - Confidence is heavily dependent on the level of conservatism of the engineering data and engineering assumptions
  - Results could be used as an input to a basic event or a single scenario in the traditional PRA process.

Risk Assessment Using Probabilistic Engineering Approach



Conclusions

- Process control is a critical factor for achieving high reliability and low system risk
- Component designers of future launch vehicle should, consider manufacturability and the feasibility of good process control in the design selection process
- An integrated process control plan should be developed upfront, and implemented throughout the different phases of the program