Evaluation of Space Shuttle Solid Rocket Motor Recovery Data, A Lesson Learned for the Ares I Launch Vehicle

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

Trilateral Safety and Mission Assurance Conference (TRISMAC)
ESA-ESTEC, Noordwijk, the Netherlands, April 14-16, 2008

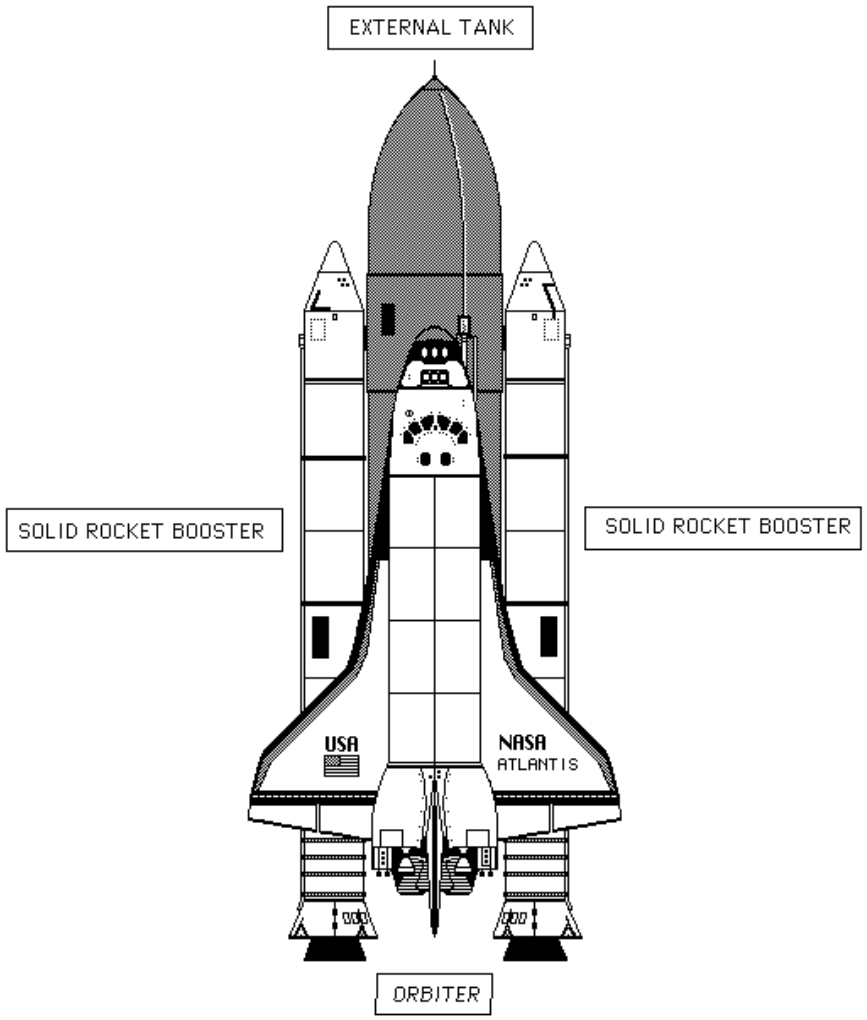
Fayssal.M.Safie@nasa.gov

Objectives

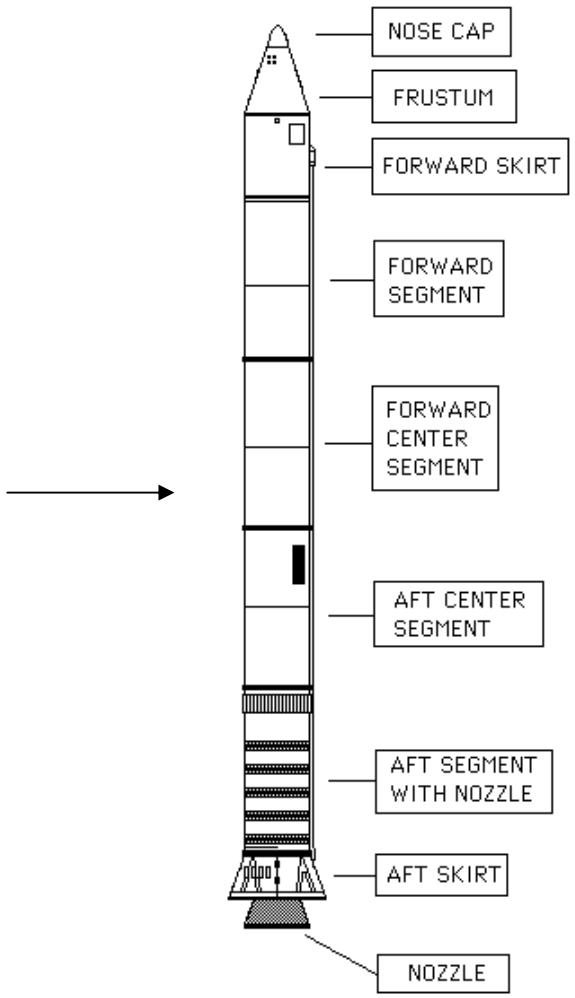
- **The objective of this presentation is to share some lessons learned from the recovery and the reusability of the Space Shuttle Reusable Solid Rocket Motor (RSRM).**
- **The information presented is based on an assessment which was part of larger task conducted by the NASA Ares project - expendability versus recovery and reusability. Specifically, the assessment included:**
  - Evaluating the general trends over time – learning curves
  - Evaluating the data characteristics with regard to design and manufacturing deficiencies
  - Evaluating the potential risk impact of loss of recovery data
  - Evaluating the potential use of the findings for the Ares I First Stage

Space Transportation System
Reusable Solid Rocket Booster (RSRB)

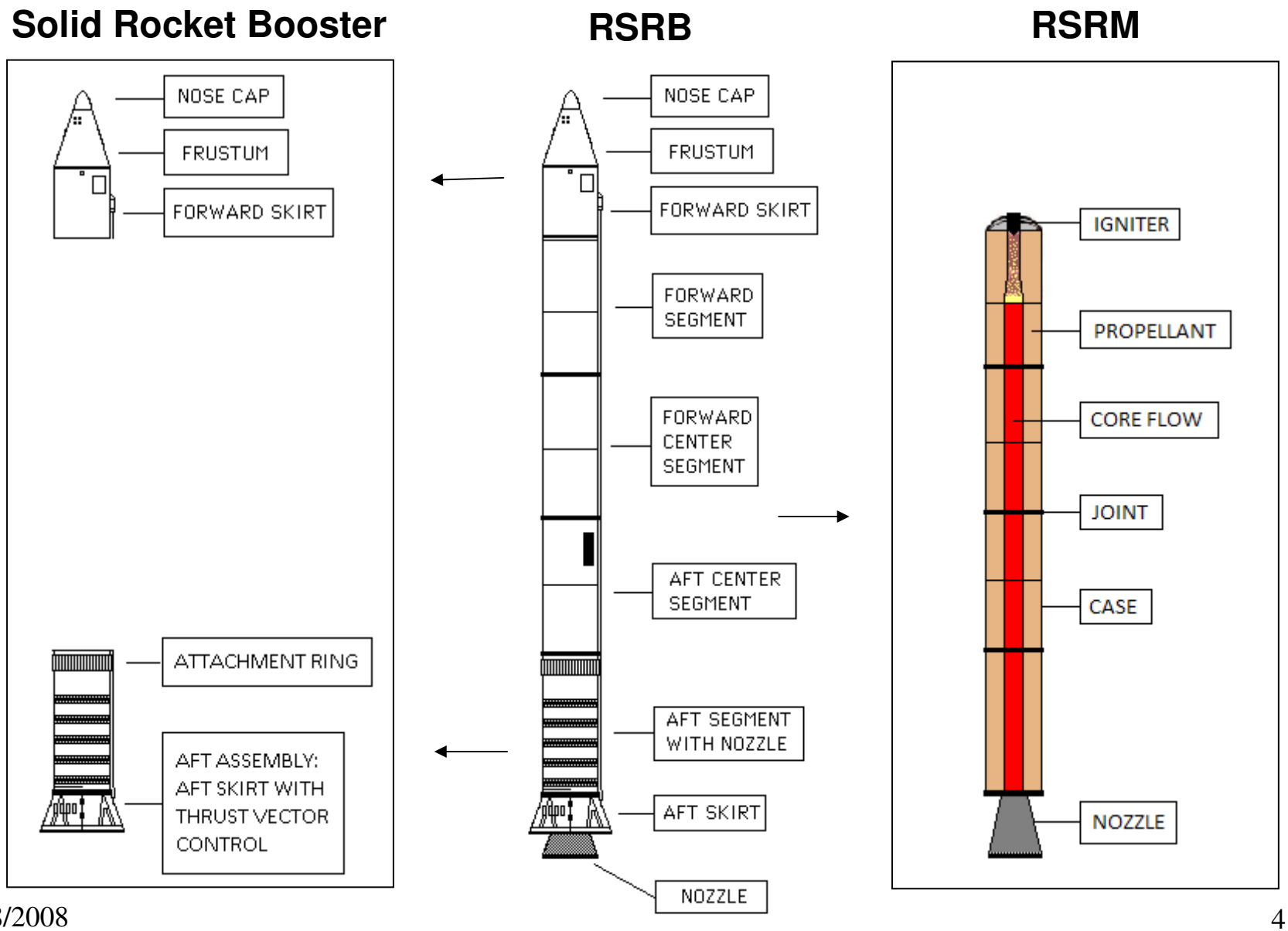
Space Transportation System



Reusable Solid Rocket Booster



Reusable Solid Rocket Booster (RSRB)



Study Limitations

- The study focused on the Reusable Solid Rocket Motor data.
- The study addressed post Challenger data only.
- Risk reduction due to Post Flight Inspection is difficult to quantify due to extreme difficulties in classification of problems that have potential catastrophic failure and subjectivity of the quantification process.

RSRM Post-Flight Assessment Report (PFAR) Screening Process

RSRM PFAR 1124

Total number of PFARs written against RSRM

RSRM PRACA ~350

All PFARs are evaluated against PRACA reporting criteria as defined in NSTS 08126. PFARs that meet the PRACA criteria are considered to be more critical

PRACA closed by corrective actions 93

PRACA reports are basically closed in one of two ways

1. **Closed by Explanation**: The item is understood to have No Significant Change in Risk to flight
2. **Closed by Corrective Action**: The risk level warrants a change to the Hardware and/or process

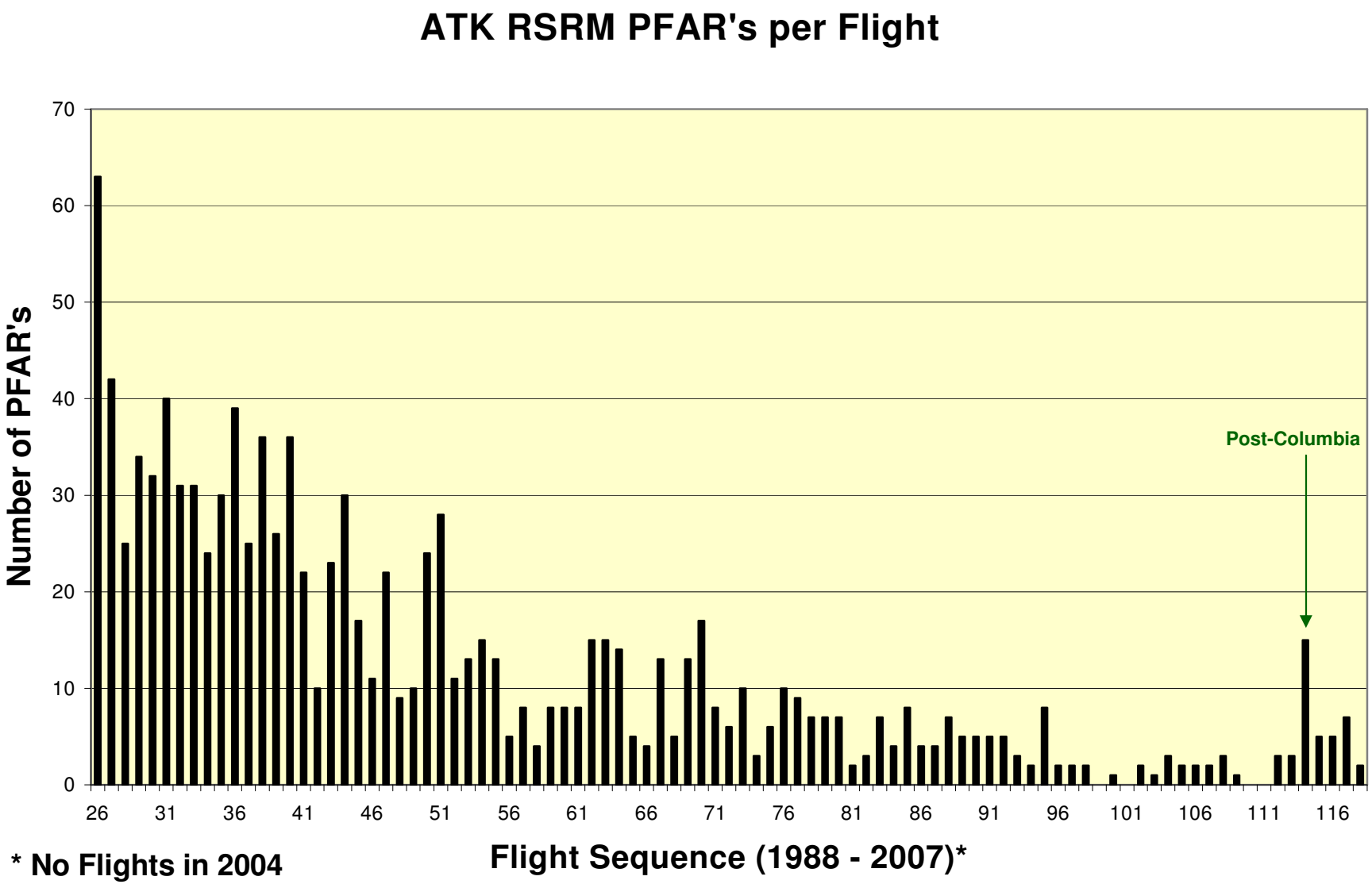
PRACA that could have propagated to Crit 1 failure (??)

Crit 1 problems that are that have been seen first in flight although they could have been seen in test

Definitions:

RSRM	**-**	**Reusable Solid Rocket Motor**
PFAR	**-**	**Post Flight Assessment Report**
PRACA	**-**	**Problem Assessment and Corrective Action Report**
Crit 1	**-**	**Criticality 1 (Catastrophic) Failure**
Ares	**-**	**New NASA launch vehicle**

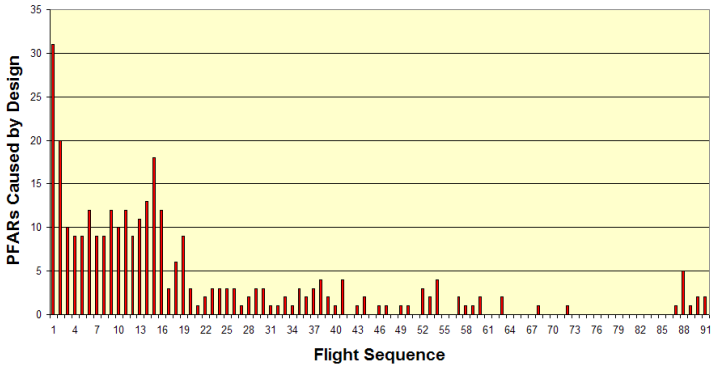
RSRM PFAR [Post Flight Inspection (PFI)]



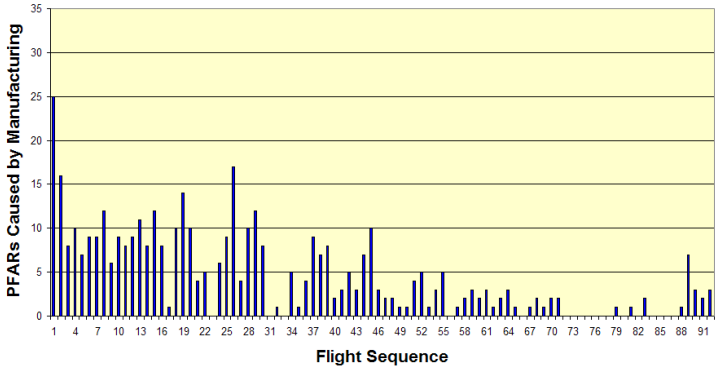
* No Flights in 2004

RSRM PFAR (PFI) Causes by Category

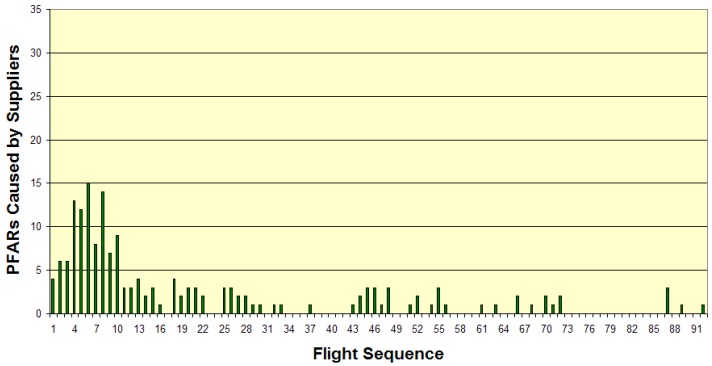
Design Causes



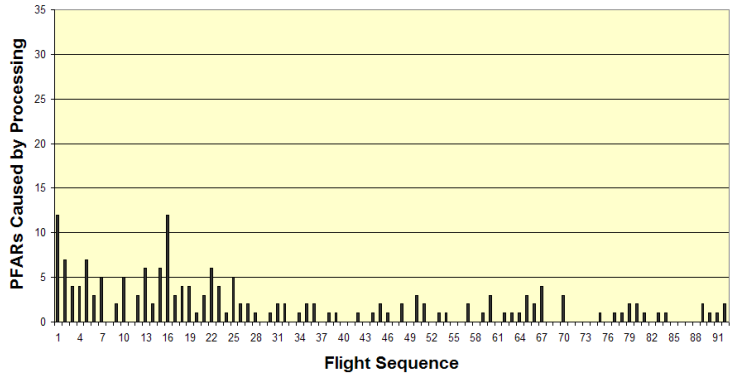
Manufacturing Causes



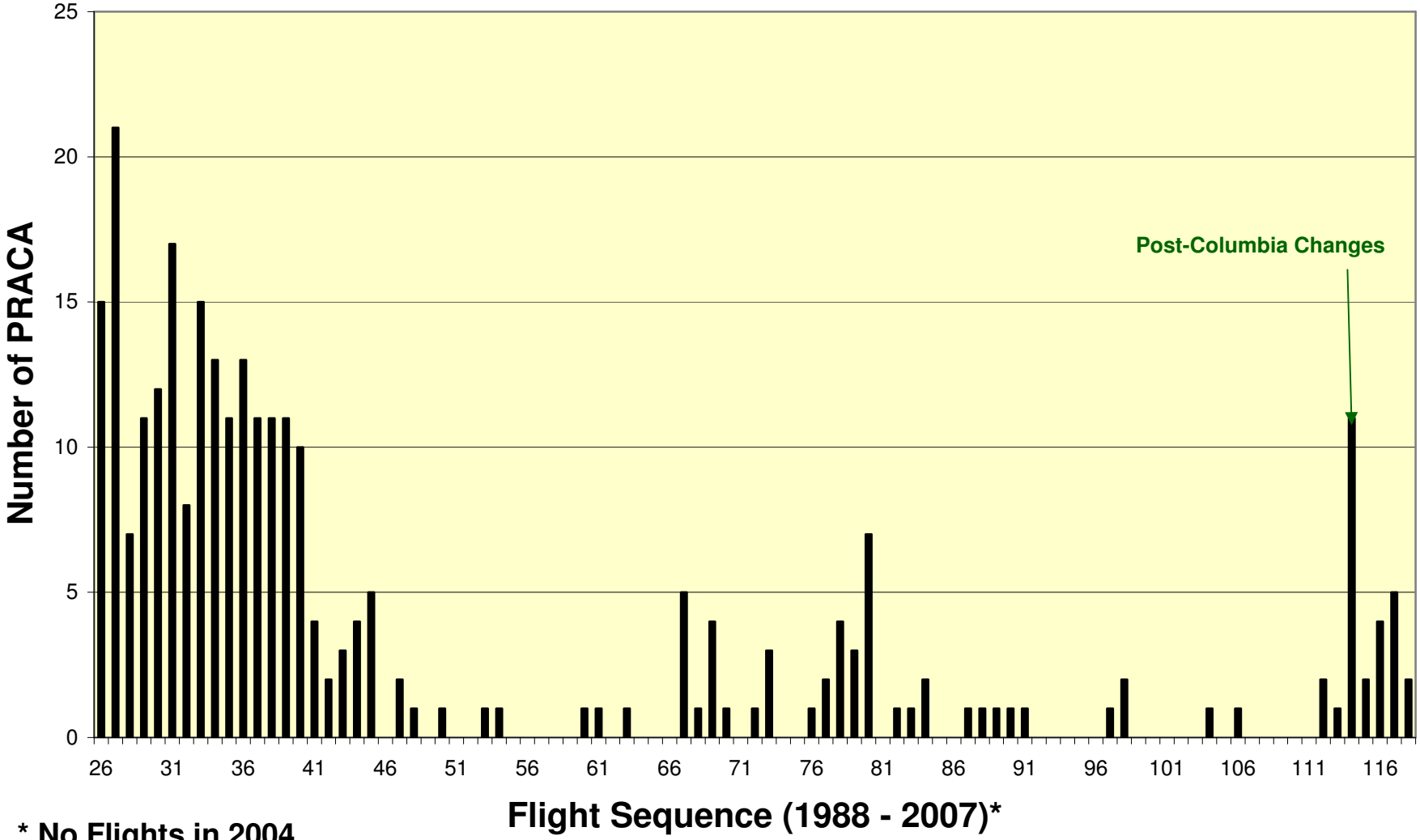
Supplier Causes



Processing Causes

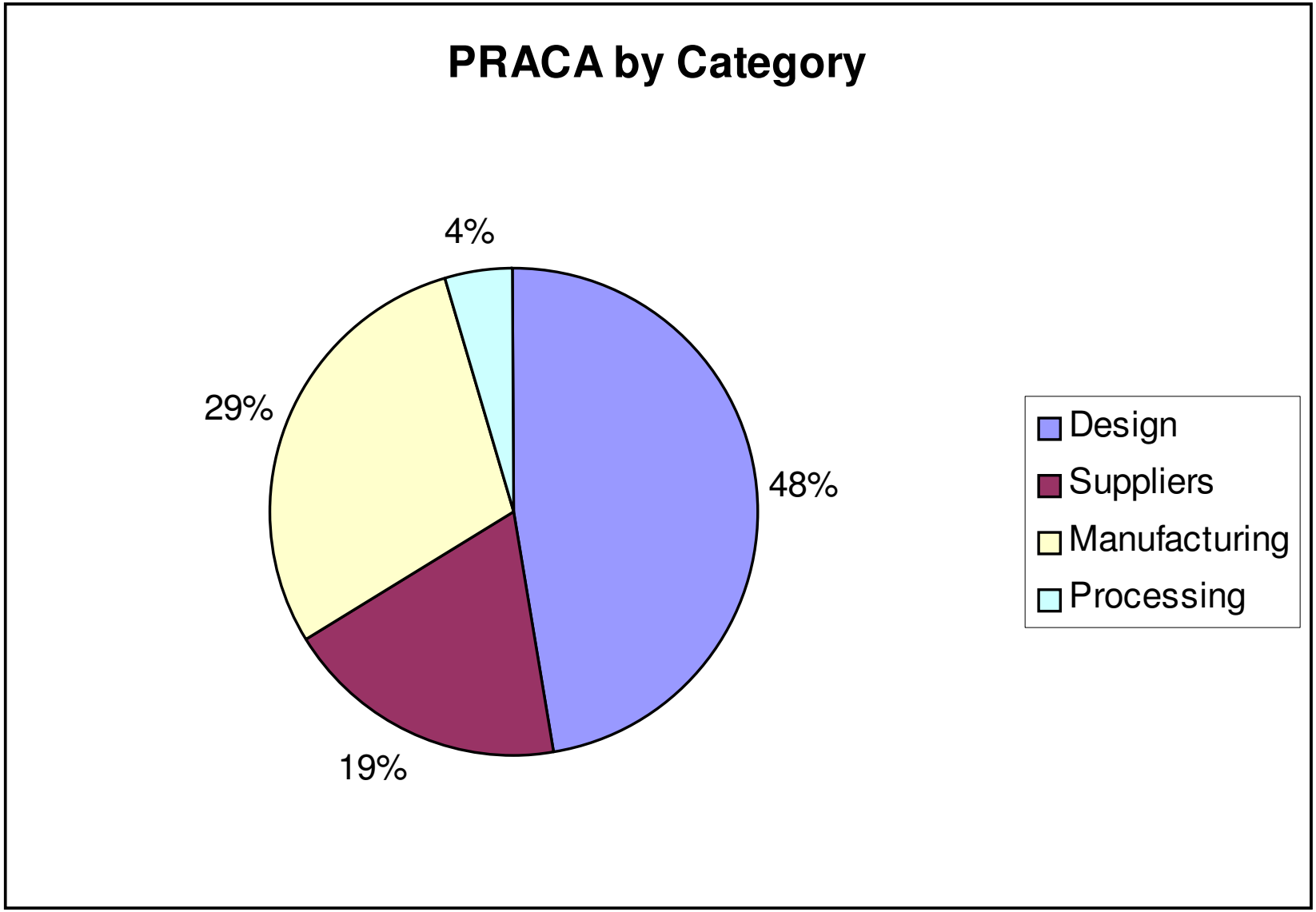


ATK RSRM Flight PRACA



* No Flights in 2004

RSRM PRACA (PFI) by Category



RSRM PFAR (PFI)– Process Creep

- **Manufacturing concerns:**
  - 35 of the 93 PRACA closed by corrective action were closed via a process change
  - Concern was raised regarding any process change that could be caused by <u>process creep</u>, defined as an out of control process that could continue to worsen without post flight evaluation as a feedback mechanism
  - 17 of the 35 process related PRACA were assessed to be potential process creep issues
    - All 17 process creep items were analyzed and, if not corrected, could have led to a reduction of margin

Post-Challenger Potential Crit 1 Case Assessed

STS	FLT	Date	RSRM	Title	Summary
79	79	9/16/1996	56B	Abnormal Carbon Phenolic Erosion Pattern on Nozzle Throat Ring and Forward Exit Cone, RSRM-56B *	SPR 292. RSRM-56B pocket erosion on the throat and forward exit cone CCP (and erosion/char margin of safety violations) may be attributed to ply angles and wrinkles in throat aft end. RSRM-49 also had pocket erosion on the throat and FEC (and erosion/char margin of safety violations). Minor pocketing was also reported on RSRM-57B. See deviation RDW-0652. Adequate margins of safety allow for pocketing. A Spacer augmented mandrel - allows for overstock and removal of any ply distortions - was incorporated. Plasma torch test bed (PTTB) sampling of aft tag ends and laser hardening material evaluation lab (LHMEL) tests - when necessary - help identify phenolic material that may have a higher propensity to pocket. See PAS 301.

* This phenomenon occurred during the SRM program and then again on RSRM-56B. Later it was observed on FSM-09 static test. Nozzle composite parts have demonstrated a high sensitivity to change over the years. The cause for the pocketing was attributed to an oven at a second tier supplier. Processing creep occurred with the oven which led to the pocketing. Without post flight evaluation the probability of detection for this issue would have been extremely low.

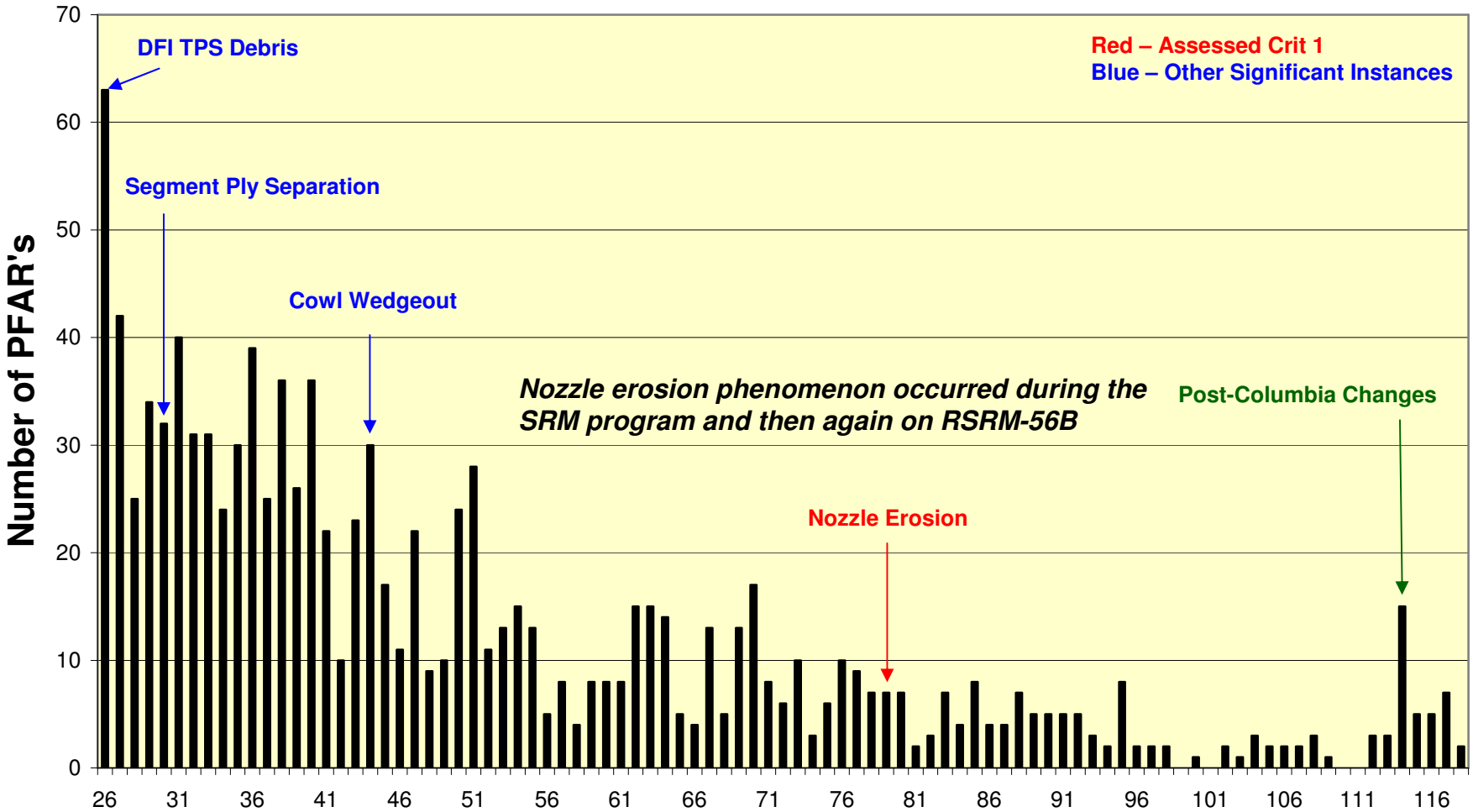
Criteria for selection of potential Crit 1 Cases: Problems that have been seen first in flight although they could have been seen in test.

Examples of Other Significant Instances/Potential CRIT 1

STS	FLT	Date	RSRM	Title	Summary
26	26	9/29/1988	1	RSRM DFI TPS Debris	SPR 114. RSRM-1 DFI TPS cap cork missing on each of the RSRM. Cork caps are tap tested: center voids are vented with 0.125-inch drill holes, edge unbond are removed and replaced with K5NA. Effective RSRM-4 all cork cap requirements were removed, cork runs are now fill with K5NA. See SPR 127.
28	30	8/8/1989	5B	Aft Center Segment Ply Separation	SPR 169. RSRM-5B center aft insulated ply separation due to contamination. The contamination was adhesive residue from yellow vinyl tape used during an unscheduled vacuum bag operation. The Methyl Chloroform residue cleaning process was not adequately performed. Corrective action required that all segments requiring usage of vinyl tape include 100% visual and black light inspection.
44	44	11/24/1991	19B	Cowl - Outer Boot Ring Erosion / Wedgeout	SPR 223. RSRM-19B cowl CCP aft end wedge outs (wash out areas) occurred during motor operation. Effects on cowl/OBR bond line and bearing protector questioned. No margin of safety violations (SPR 94). Wedge out areas vs. non-wedge out areas showed no appreciable difference in char line depth. In-addition corrective action to change the cowl CCP ply angle (RSRM-32) from 0 degrees to -50 degrees (ECP-2674) was to improve the erosion consistency, reduce ply lifting, and wedge out potential.

RSRM PFAR (PFI)

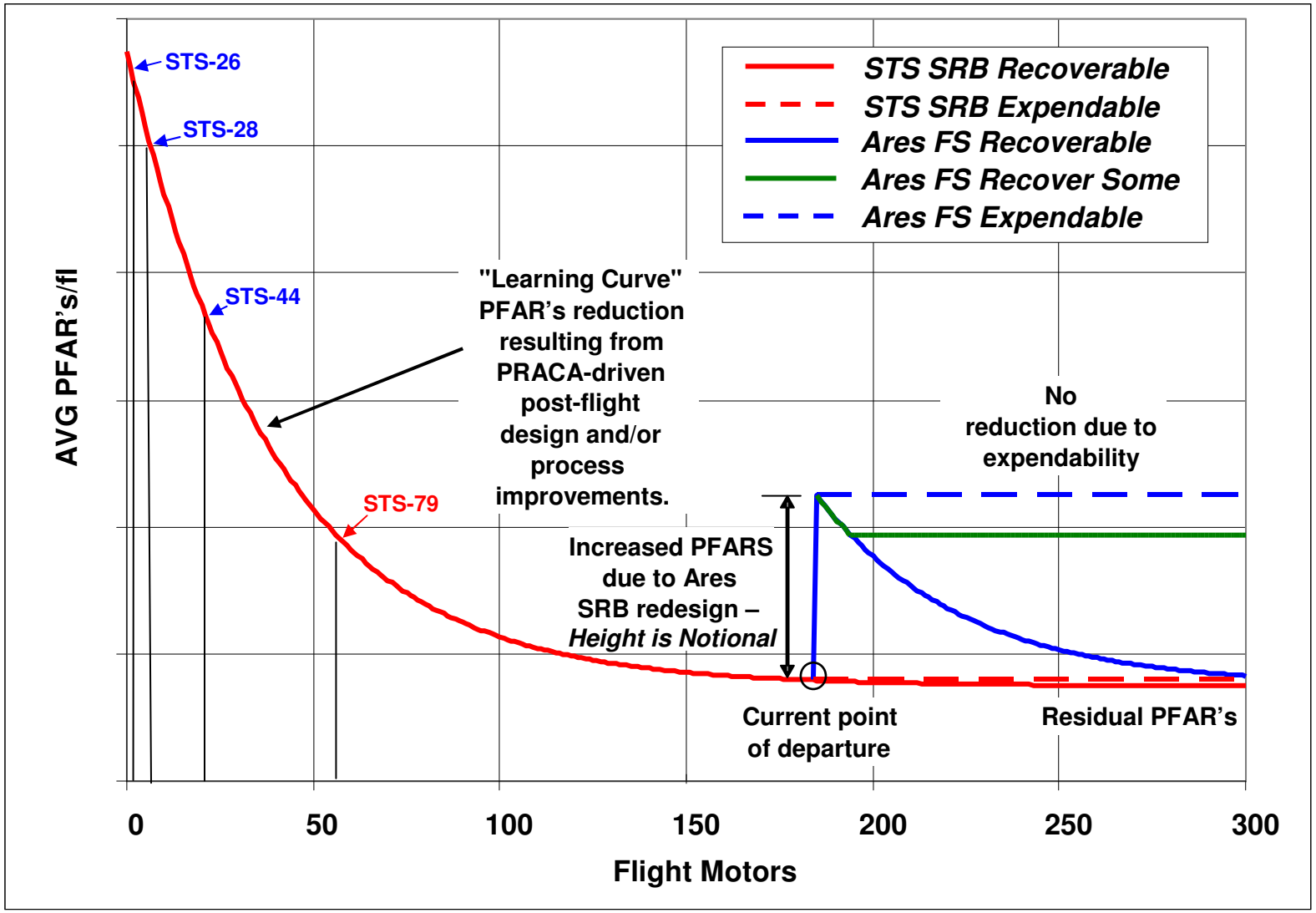
ATK RSRM PFAR's per Flight



* No Flights in 2004

Flight Sequence (1988 - 2007)*

Post Challenger Notional Summary Trend



Red STS Numbers – Assessed Crit 1
Blue STS Numbers – Other Significant Instances

Risk Quantification of Potential Crit 1 Cases

- Evaluation of PFI history showed that quantification of the risk reduction due to recovery and inspection of the RSRM is extremely difficult and could be misleading (depending how you treat the post flight inspection data) .
- Preliminary assessment of post-Challenger Crit 1 incidents that would have had potential propagation to catastrophic failure showed some RSRM risk reduction due to post flight recovery and inspection
- Other incidents that have potential Crit 1 propagation could possibly be found if a more comprehensive evaluation of the PFI data, including the pre-Challenger data, were performed.

Major Observations and Findings

What have we learned?

- **PFI data trend charts showed an obvious significant trend (steep learning curve) early on in the flight program**
- **Potential catastrophic failures were caught prior to catastrophic effects**
- **Loss of PFI data will:**
  - **Result in a major impact on obsolescence (motor will continue to change overtime)**
  - **Reduce the chance of identifying new potentially critical causes not identified initially by hazard analysis (Risk increase)**
  - **Reduce the chance of identifying new potentially critical failure mode causes not identified initially by the FMEA. (Risk increase)**
- **Significant changes were made due to information from recovered hardware regarding design and manufacturing deficiencies**
- **PFI data supported a significant effort by NASA at ATK throughout the SSP to enhance process control and implement a material finger printing program**

Major Observations and Findings

What have we learned?

- **Categorization of the PRACA subset of the PFAR data into design, manufacturing, processing, and supplier, indicated that:**
  - **Design issues accounts for a high percent of problems in flight.**
  - **Ground testing might be limited and is not sufficient to account for all motor to motor variability and the system dynamic environment**
  - **There is a room for potential improvement in the current ground static testing**

Recommendations For Ares I

- Based on the significant amount of learning gained from the Space Shuttle RSRB PFI, and given the Ares First Stage design changes, material changes, and process changes:
  - Recommend Post Flight inspection (PFI) is performed for Ares first stage for some specific number of flights
    - Allows sufficient data gathering required to go through the steep part of the learning curve we experienced in the Shuttle Program see PFI trend chart)
    - Reduces the high risk expected early on in the program due to the significant design and process changes.
    - Helps in addressing the challenge of meeting the loss of mission and loss of crew (LOM/LOC) requirement
  - Recommend continuous enhancement in process control and ground static testing including consideration for "bounding case" testing to avoid the high rate of in-flight design and process problems similar to that seen in the Space Shuttle RSRB early on in the program

Thank you for listening
Any Questions?

Case I - First Stage LOM impact
1 PFI report with Potential CRIT 1 Propagation

- **Potential Risk impact due to RSRM/SRB PFI data loss:**
  - **Number of Motors flown since STS-51L = 184**
  - **Number of Severity 5 PRACA (potential of Criticality 1 failure) = 1 incident (Other potential CRIT1 instances could possibly be found if more comprehensive evaluation of the PFI data is performed)**
  - **If were not corrected, the delta risk of motor failure, under an optimistic assumptions of 1/100 chance of these potential Crit 1 instances causing a catastrophic failure, is 5.435E-05 (1/18,400).**

    A 1/18,400 risk increase for the RSRM/SRB roughly translates to a delta increase in risk of 6.5% for the first stage, and about 2% for Ares I (See next chart for calculations)

Case I - First Stage LOM impact

TPM	First Stage			ARES I		
	Requirement	Estimates		Requirement	Estimates	
		Case 0	Case I		Case 0	Case I
LOM	1/1,675*	1/1,200*	1/1126	1/500*	1/358*	1/351
LOC	1/11,000	1/8,000	1/7,510	1/3,200	1/2,386	1/2,339

Comments:

1. LOM values for the requirement and for Case 0 shown with an asterisk were provided by the Probabilistic Risk Assessment (PRA) Team/Vehicle Integration (VI).
2. Estimates for FS and ARES I Case I were derived using the 1 PRACA report with CRIT I propagation potential.
3. All LOC estimates were derived from the LOM Equivalent in the chart above through the use of a Catastrophic Failure Fraction of 15% also provided by the PRA Team/VI.
4. Other incidents could possibly be found if more comprehensive evaluation of the PFI data is performed (including the pre-challenger data)