NDE Considerations for Reusable Liquid Rocket Engines

K. Elliott Cramer

NASA Engineering & Safety Center

Chief Engineer - Langley

Outline

- Space Shuttle Engines and Reusability
- Examples from Shuttle of NDE for reusable engines
  - Space Shuttle Main Engines (SSME)
  - Orbital Maneuvering (OM) & Reaction Control Systems (RCS)
- Certification of NDE Techniques
  - NASA Standard 5009C
- Reducing NDE Cost (Time) through Emerging Technology
  - Inspection Automation
  - Artificial Intelligence (AI), Machine Learning (ML) & Automatic Defect Recognition (ADR)
  - Model Assisted Probability of Detection (MAPOD)

Interesting Facts

- May 19, 1975 (50+ years ago), 1st space shuttle main engine test; did not feature full ignition; “burp” test (less than 1 second duration).
- No space shuttle mission EVER FAILED due to main engine malfunction. The only shuttle (STS-51-F) to experience an early engine cutoff was able to reach orbit and complete its mission.

April 12, 1981: Launch of the First Shuttle Mission

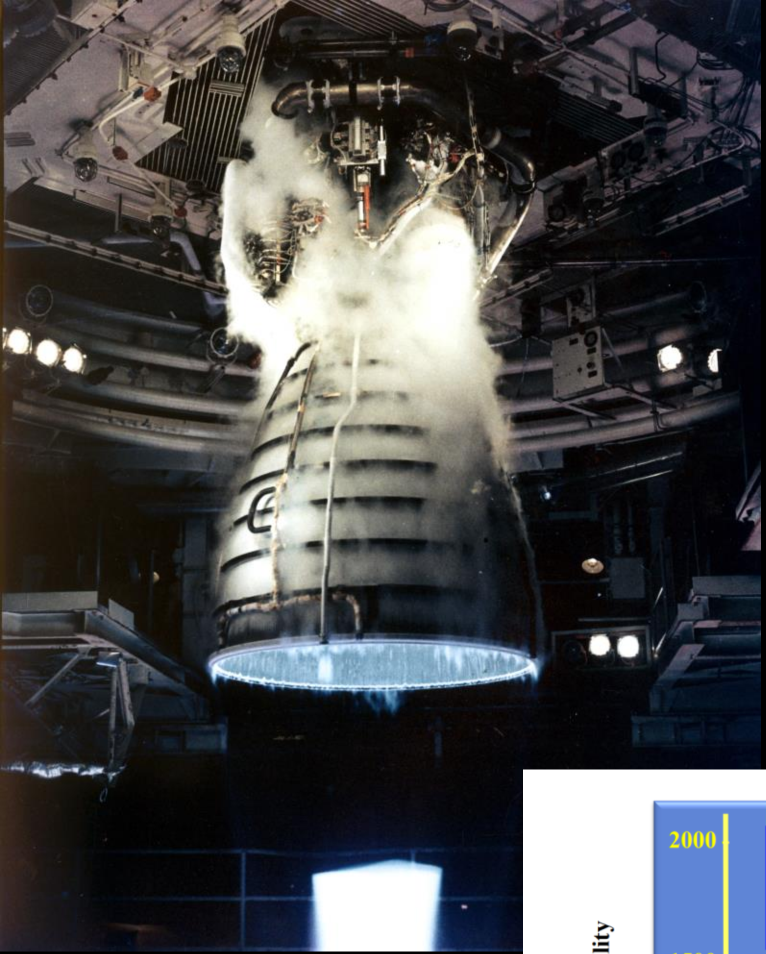
Other Interesting Facts

- Discovery: 39 missions.
- Atlantis: 33 missions.
- Columbia: 28 missions.
- Endeavour: 25 missions.
- Challenger: 10 missions.

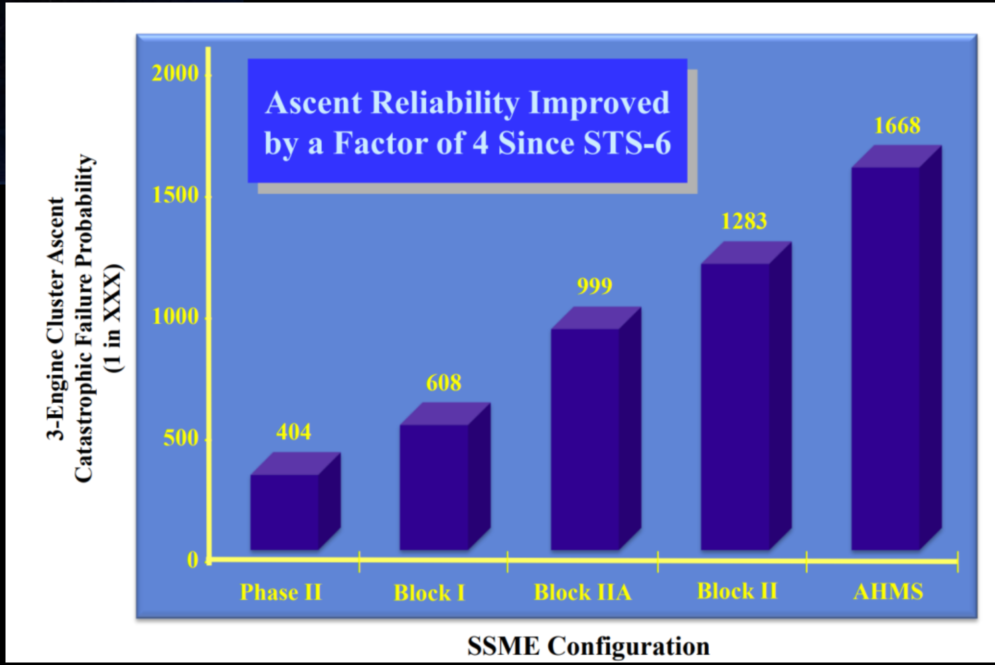
- Over 30 years.
- Average: 8 flights / year
- Most 9 flights in a year (1985) – next year lost Challenger

July 21, 2011: Final Space shuttle (Atlantis STS-135) touches down at NASA's Kennedy Space Center Shuttle Landing Facility.

Space Shuttle Main Engines Continuous Improvements



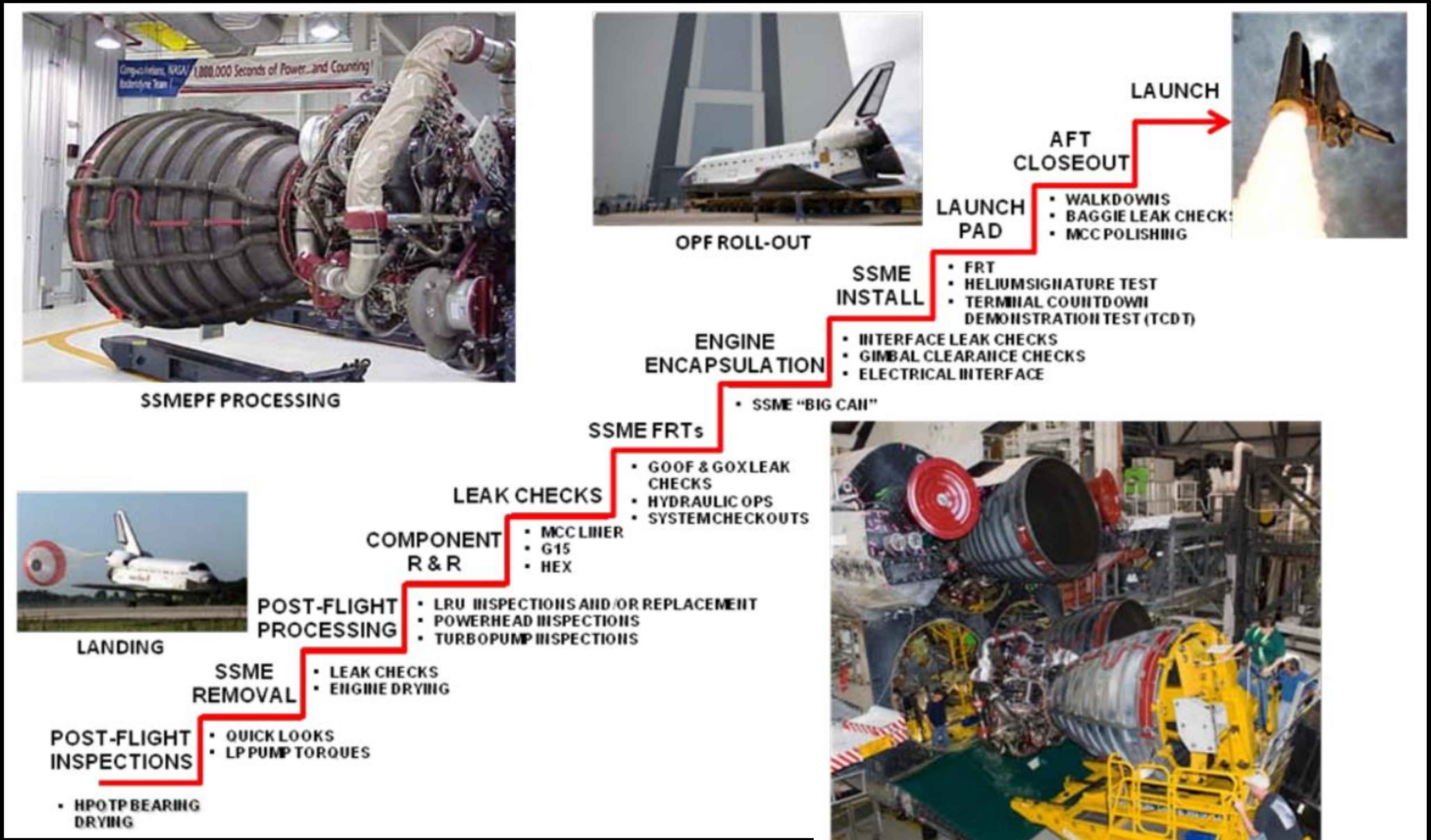
With the increases in reliability and durability of components, maintenance has also been significantly reduced. A major portion of the maintenance reduction came with the incorporation of the Block I and Block II high pressure turbopumps. ***The turbopumps do not have to be removed after flight for inspections, eliminating a significant amount of engine disassembly and reassembly effort***.*



*Van Hooser, Katherine, and Bradley, Douglas. "Space shuttle main engine-The relentless pursuit of improvement." AIAA space 2011 conference & exposition. 2011.

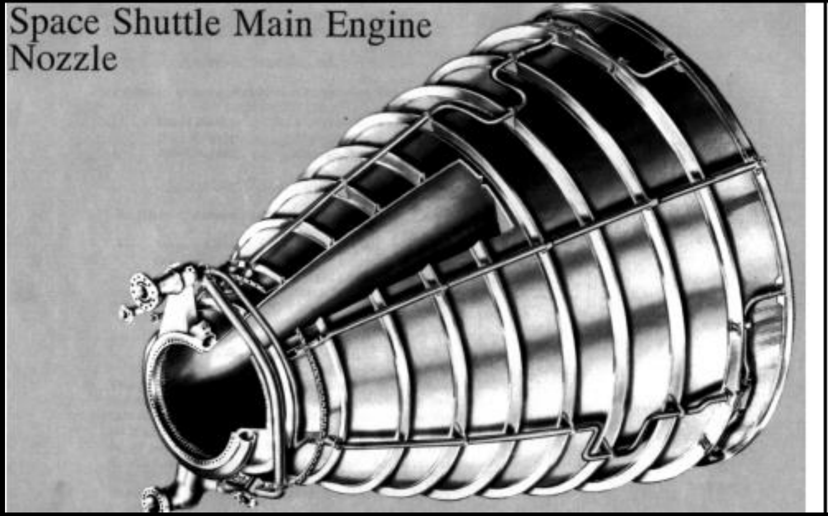
Typical SSME Processing Flow at Kennedy Space Center

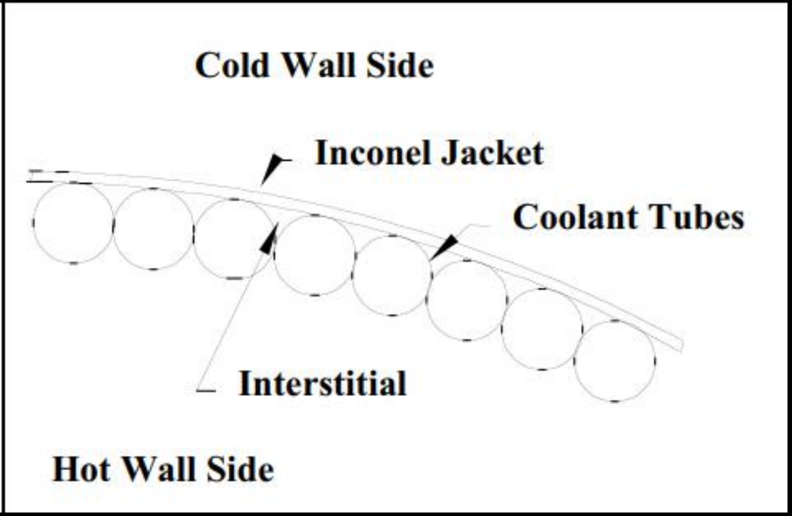
“SSP maintenance and operations must recognize that the Shuttle is not an ‘operational vehicle’ in the usual meaning of the term.” – **Shuttle Independent Assessment Team (1999)**



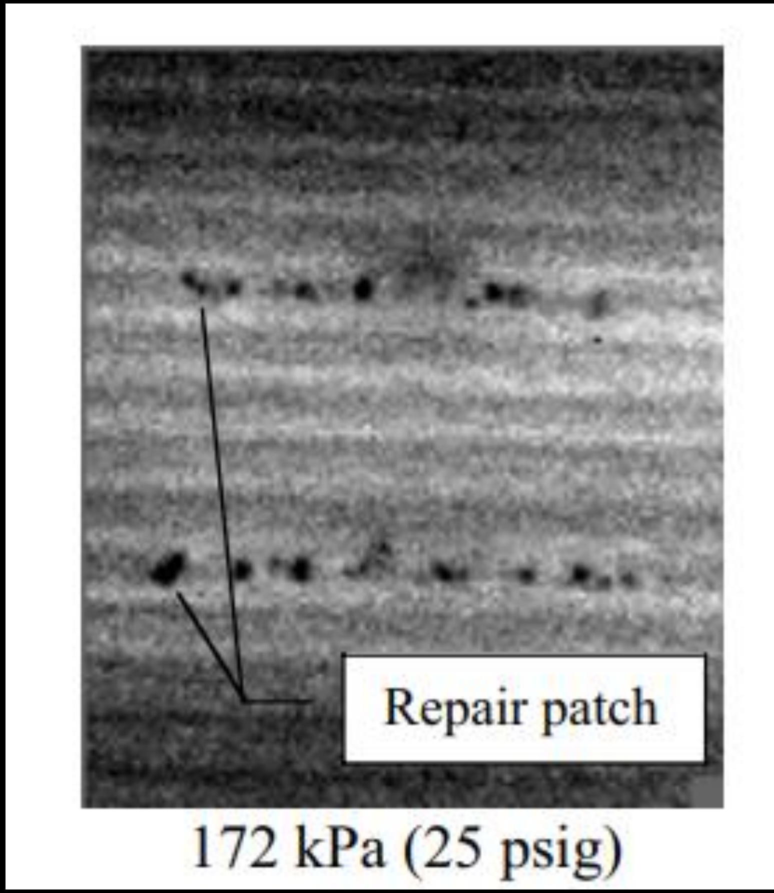
Van Hooser, Katherine, and Bradley, Douglas. "Space shuttle main engine-The relentless pursuit of improvement." AIAA space 2011 conference & exposition. 2011.

SSME Cooling Tube Leakage





IR Image of Pressurized Nitrogen Flow in Tubes

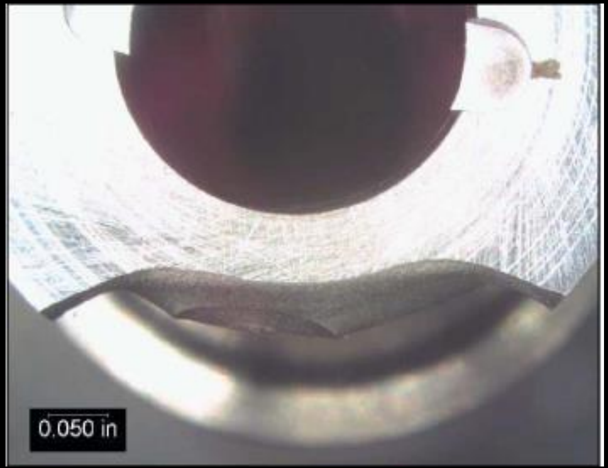


3 Types of Defects

- Poor or incomplete bonding of the tubes to the structural jacket
- Leaks into the interstices between the tubes and jacket
- Leaks into the inner “hot wall” or “flame” side of the nozzle.

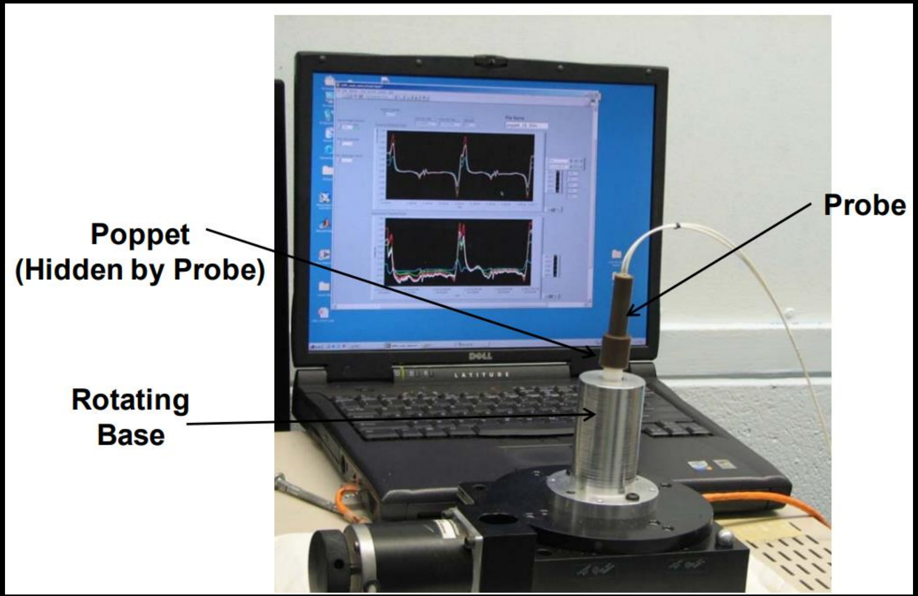
Walker, James L., et al. "Thermographic/Nondestructive Evaluation of the Space Shuttle Main Engine Nozzle." *Proceedings of The 4th Conference on Aerospace Materials, Processes, and Environmental Technology*. 2001.

SSME Flow Control Valve Poppet



440A Steel body cracked due to high cycle fatigue
No cracks found in the original acceptance inspections

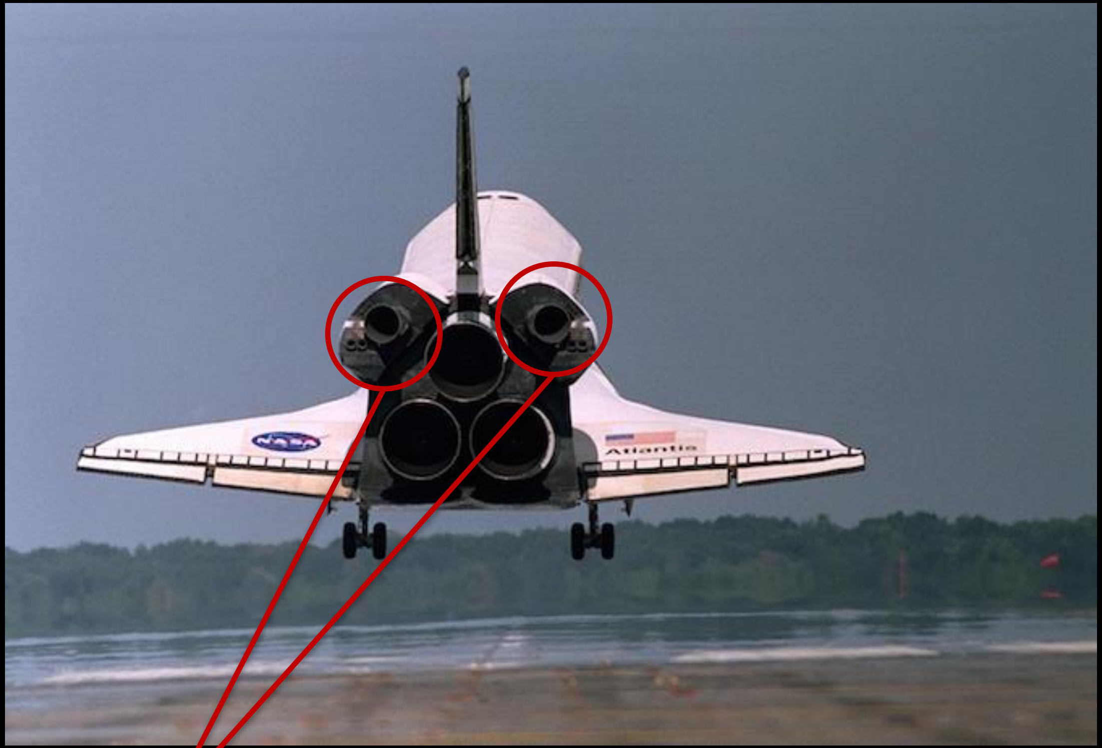
Eddy Current Inspection System Developed

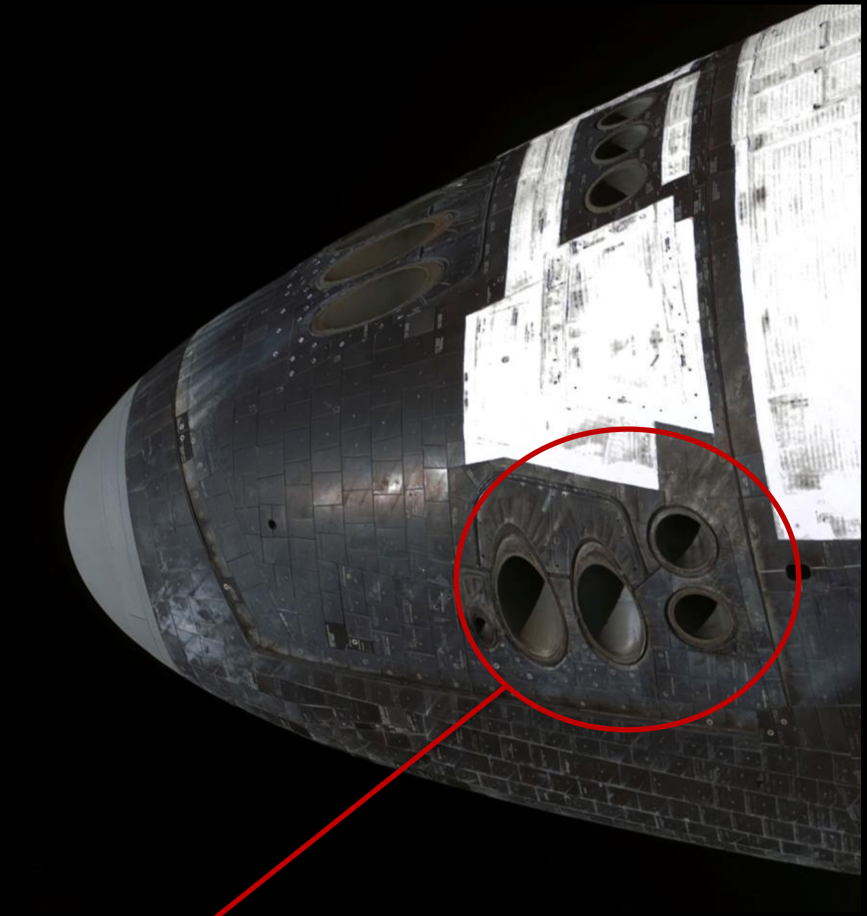


- Limited specimen POD analysis conducted
- Inspection system can find cracks greater than 0.030 inches (0.76 mm) with probability exceeding 0.90.
- This capability has been established at a 95 percent confidence level.
- Estimated false call rates at this threshold level are small (< 0.002)

Koshti, A., Ruffino, N., Wincheski, R., Prosser, W., Winfree, W., Russell, R., ... & Landy, J. (2010, May). Nondestructive Crack Detection in a Fuel System Component. In *2010 Aircraft Airworthiness and Sustainment Conference*.

OMS & RCS





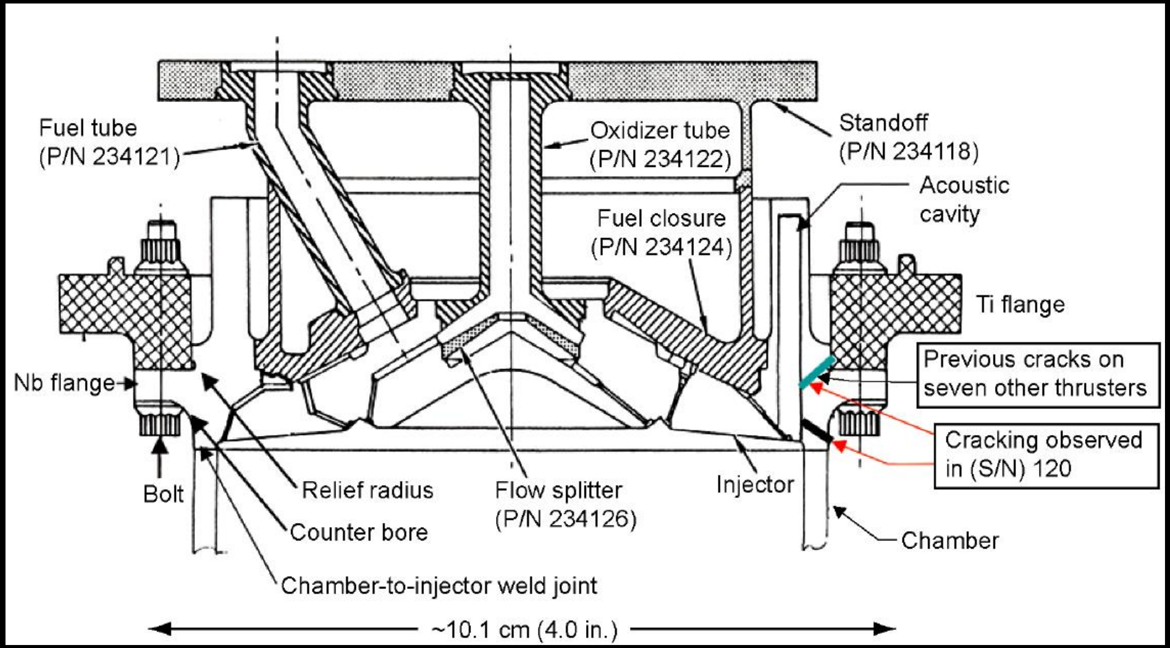
OMS

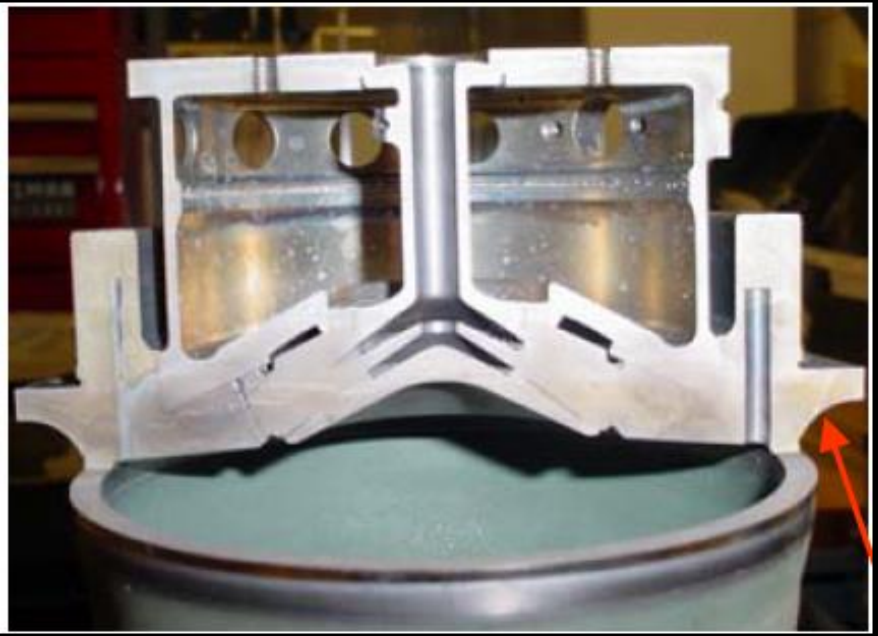
- 2 OMS thrusters on the orbiter's aft fuselage
- 6,000 lbf per thruster

RCS

- 38 Primary (870 lbf) thrusters
- 6 Vernier (20 lbf) thrusters

RCS Thruster Cracking

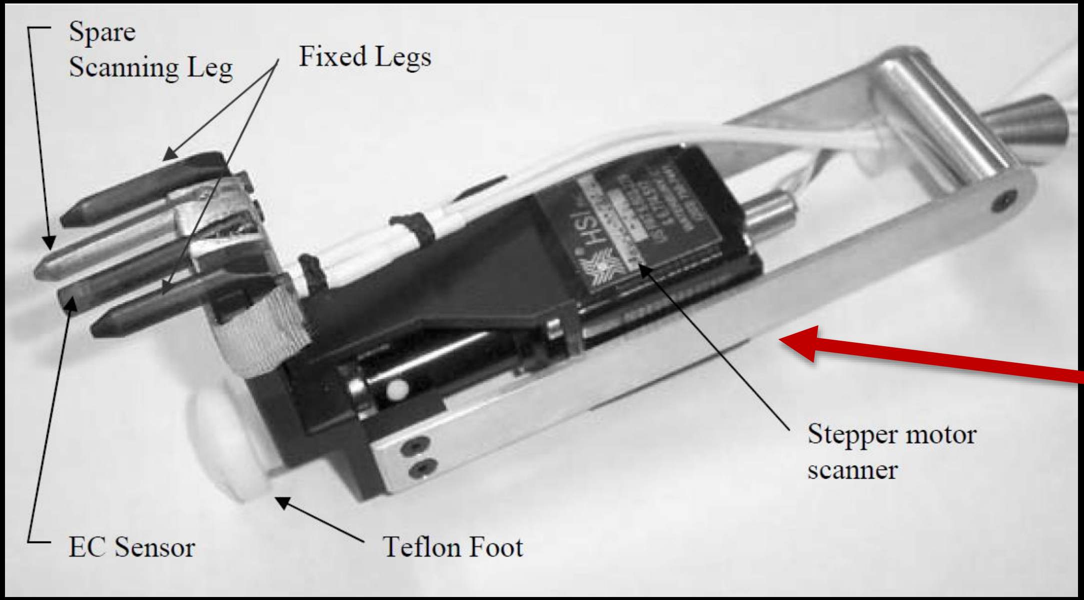


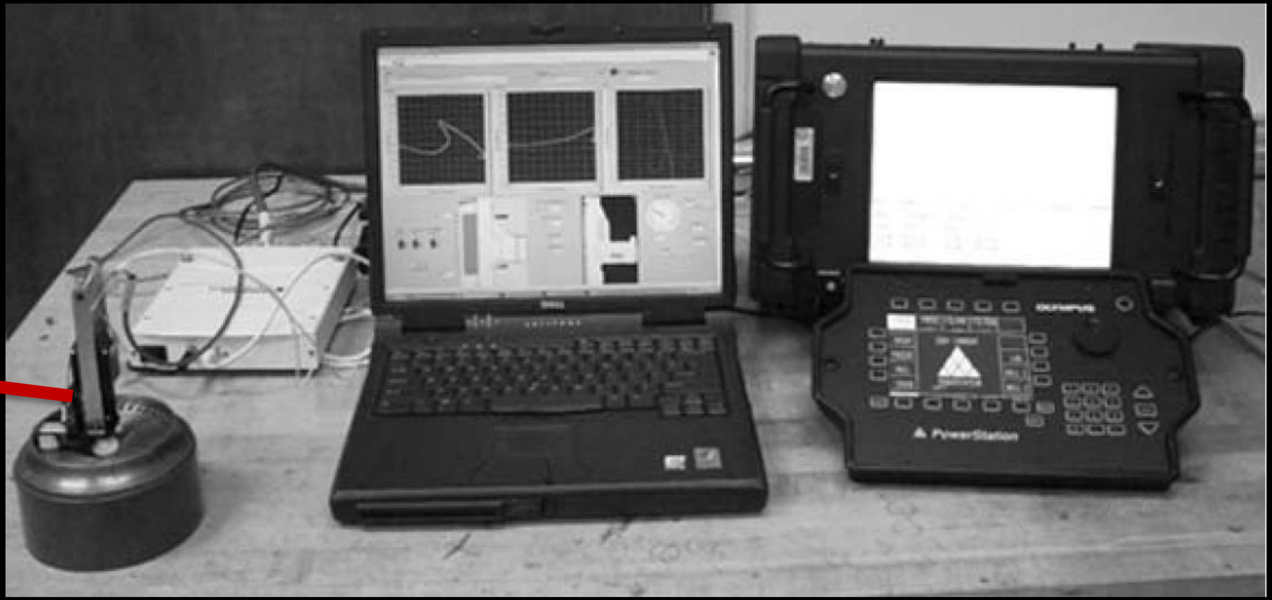


- Thruster Cracks in 9 of 16 injector flange bolt hole were found during thruster refurbishment
- No external access to the bolt holes
- In situ NDE was needed to eliminate the need to for disassembly for inspection

MacKay, Rebecca A., et al. *Reaction Control System Thruster Cracking Consultation: NASA Engineering and Safety Center (NESC) Materials Super Problem Resolution Team (SPRT) Findings*. (2005). NASA/TP—2005-214053.

RCS Thruster Cracking





The system was extensively tested on both simulated and naturally occurring flaws, showing a signal to noise ratio better than 3 to 1 for flaws as deep as 0.060” away from the acoustic cavities.

Wincheski, Buzz A., John W. Simpson, and Ajay Koshti. "Development of Eddy Current Techniques for the Detection of Cracking in Space Shuttle Primary Reaction Control Thrusters." (2007). NASA/TP-2007-214878

Lessons Learned from Shuttle Not Limited to Engines

- The Shuttle program underscored the challenges in inspecting complex materials like the external tank's foam insulation and the reinforced carbon-carbon panels due to their unique properties and variations
- Many existing (COTS) inspection methods were found to be insufficient, prompting the need for enhanced techniques for detecting subsurface defects
- The Shuttle program demonstrated that there is growing gap between current NDE capabilities and the increasing complexity of future space systems, highlighting the need for accelerated development of advanced NDE technologies
- NDE is usually an after thought (sometime an after accident) – therefore there continues to be the need to have NDE considered earlier in design and testing cycles and accepted as a valued and required part of the design, manufacture and lifecycle management for space components
  - Design for Inspection*

*P. Juarez, S. Dauria, S. Lonne, B. Clausse, H. Tat and J. Bingham, Design for Inspection: A Formalized Approach to Evaluating the Inspectability of Aerospace Structures Early in the Design Process, *Society for the Advancement of Materials and Process Engineering Conference*, Long Beach, CA, 2024, https://doi.org/10.33599/nasampe/s.24.0168

NASA STD-5009C

Nondestructive inspections of fracture-critical hardware **shall** detect the initial crack sizes used in the damage tolerance fracture analyses with a capability of minimum 90% probability of detection at a 95% confidence level, known as 90/95.

Two NASA NDE Classifications:

- Standard NDE
  - NDE techniques: eddy current, fluorescent penetrant, magnetic particle, radiography, and ultrasonics
  - Established minimum detectable crack sizes
  - Formal Probability of Detection (POD) determination not required, only a demonstration of capability on simulated or real crack-like flaws
- Special NDE
  - Flaw sizes smaller than standard established critical flaw size
  - Includes techniques other than those listed above
  - Formal 90/95 POD determination required by specific inspector(s) that will perform inspection
  - Can use either Point Estimate, LS-POD, or MIL-HDBK-1823A POD methods

What about a new “Standard NDE”?

- MIL-1823A compliant POD study of a minimum of 10 inspectors that form a representative sample of inspectors
- Individual inspector analyses shall be performed in accordance with MIL-HDBK-1823A and estimated a90/95 flaw sizes for the individual inspectors shall be reported
- Individual inspector Probability of False-Calls (POF) shall be reported and are recommended to not exceed 1% POF with 50% confidence
- Standard NDE flaw size shall be estimated as a function of the average and standard deviation of individual inspector a90/95 flaw sizes, and it shall represent the flaw size that 90% of inspectors are expected to demonstrate at least 90/95 detection capability

What is Involved?
Typical POD (MIL-HDBK-1823A)

- “Specimens should **closely resemble the subject parts** that are being tested by the demonstrated NDE system”
- “Flaw location and orientation are significant geometric considerations for most inspection techniques (for example, corner flaws versus surface cracks.) **Flaw locations in specimens should be oriented and positioned to represent cracks that have been recorded in actual parts**… The initial geometry of the specimen should allow the insertion of **targets of the shape and size in the specified locations**. The specimen should be designed such that the targets can be inserted, and the final geometry obtained by machining or other forming methods that will not change the target characteristics (size, shape, and orientation and intended location)”
- “At **least 60 targeted sites** if the system provides only a **binary, hit/miss** response and at least 40 targeted sites if the system provides a **quantitative target response**. These numbers are minimums. For binary responses, 120 inspection opportunities will result in a significantly more precise estimate.”

Reducing NDE Cost (Time) through Emerging Technology - MAPOD

- POD is EXPENSIVE!!!!!
  - Lots of difficult to make samples
  - Independent verification of the flaws
  - Possibly multiple inspectors
- POD “estimated” from results of NDE demonstration tests using a statistical sampling of specimens with **representative flaws** of known sizes, and may include **multiple inspectors**
- MAPOD (MIL-HDBK-1823A – Appendix H) uses simulation models and potentially limited experimental data to estimate the probability of an inspection system to detect a defect

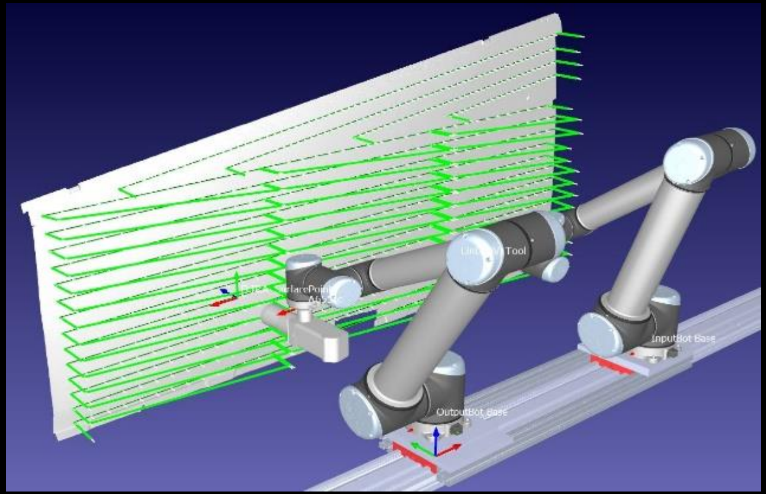
MAPOD Considerations

“***All models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind.***” – George E. P. Box

- Considerably less experimental requirements especially for hard to fabricate defects
- “In an application of the unified approach to MAPOD, ***one needs to consider both limits to accuracy, statistical uncertainty and uncertainty in modeling predictions to make an overall assessment of the accuracy of the POD predictions***. Hence the accuracy required of the model will be a consequence of the particulars of the problem and the accuracy needed in the POD.”*

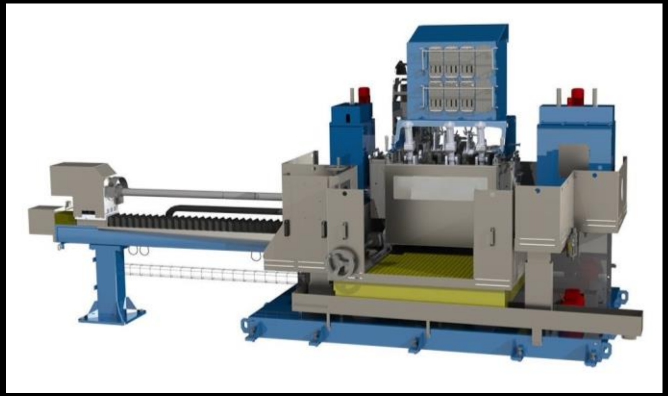
*Thompson, R. Bruce, et al. "Recent advances in model-assisted probability of detection." 4th European-American workshop on reliability of NDE. No. LF99-9094. 2009.

Reducing NDE Cost (Time) through Emerging Technology - Autonomous / Robotic Inspections



Robotic Inspection System (artist concept)

Fully Automated Inspection Station (artist concept)



Robotic Inspection Crawler(artist concept)

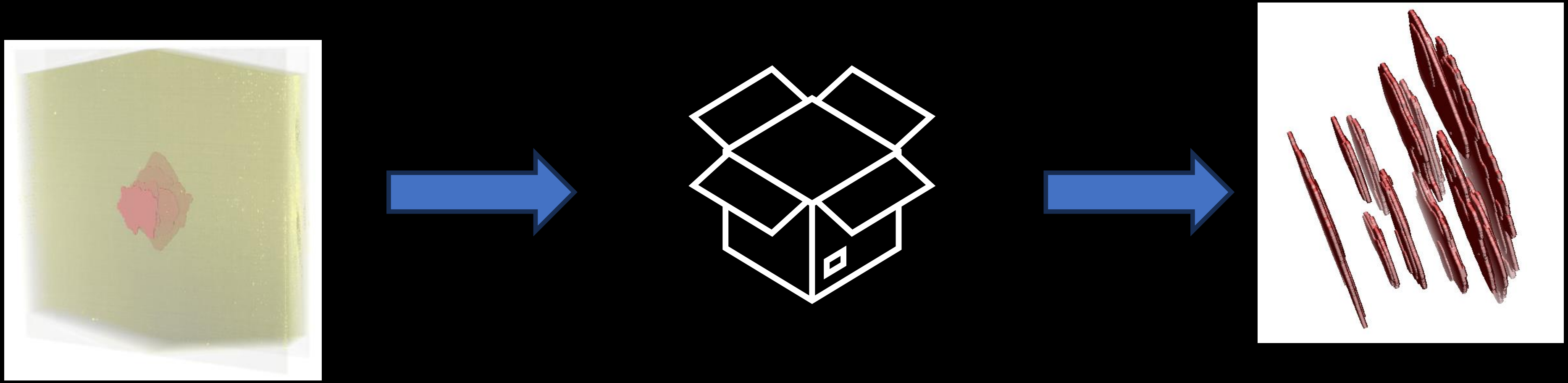
Multi-axis Automated Fiber Placement (AFP) Robot with *in situ* Inspection

Autonomous / Robotic Inspections Considerations

- Speed and Manpower Reduction
  - Inspector Training
- Reproducibility
  - Good or Bad
- Volume of Data Produced
  - Built in Analysis
- System Complexity
  - Including self-diagnostics
- ROI – Is the part volume there?

Reducing NDE Cost (Time) through Emerging Technology - AI / ML / ADR

Automatic Defect Recognition (ADR) in NonDestructive Evaluation (NDE) leverages NDE data and artificial intelligence to automate the detection and classification of defects in materials. This approach aims to improve efficiency, accuracy, and consistency compared to manual inspection, particularly in high-volume manufacturing and critical applications.

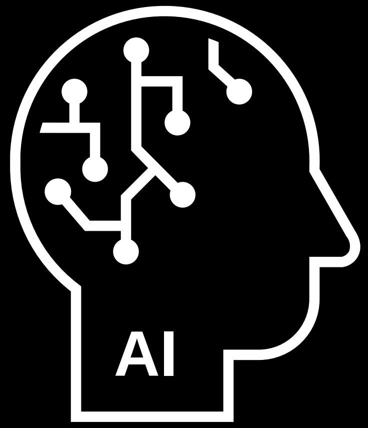


Automated Interpretation of CT Data
via convolutional neural network (CNN)

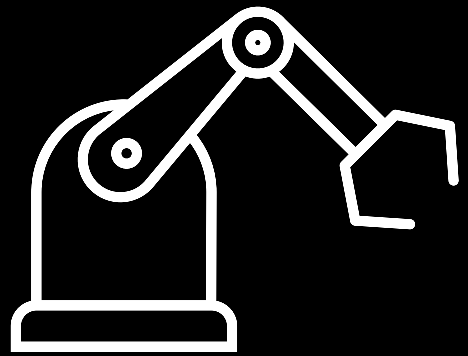
AI / ML / ADR Considerations

- Reduces Human Variability
- Increases Analysis Speed
  - Especially for Large Data Volumes
- Scarcity of Training Data (hopefully)
  - Related to why doing POD is so expensive
  - Could be model based training – see MAPOD Considerations
- Validation of ADR Systems (especially genetic algorithms)
- Training of Inspectors

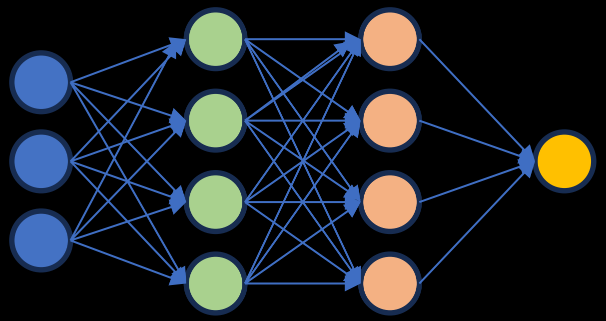
It's All About Risk!



5	10	16	20	23	25
4	7	13	18	22	24
3	4	9	15	19	21
2	2	6	11	14	17
1	1	3	5	8	12
	1	2	3	4	5



Autonomy

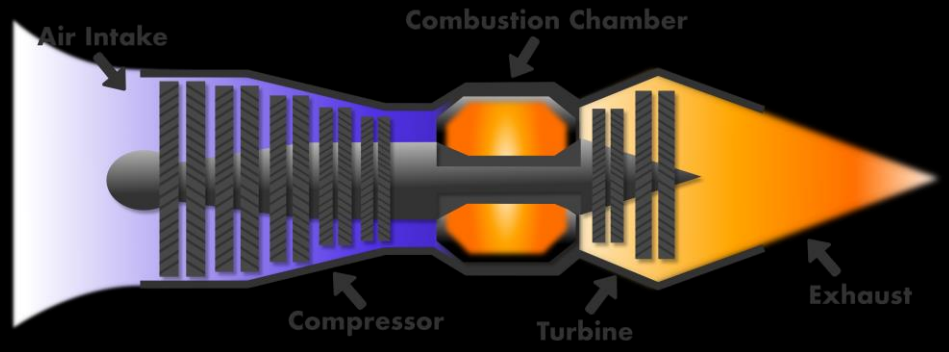


Model Assisted

Questions

Backup

Greater Reusability & NDE



- Safe-Life Approach (NASA STD-5019)
- Heavily inspected during manufacture
- Large safety margins to account for "unknown unknowns"
- Heavy maintenance after each use
  - Heavy reliance on inspections
  - Limited Life Parts (some 1 mission)
  - On Condition Parts
  - "Find it, Fix it"

- Mostly Fail-Safe Approach
- Heavily inspected during manufacture
- Well understood critical flaw sizes
- Maintenance schedule based on fracture mechanics & fleet leaders
  - Limited Life Parts (usually based on hrs.)
  - On Condition Parts*
  - Trend Monitoring
  - Major Periodic Inspection Schedule
  - Core Zone Inspection Schedule
  - Hot Section Inspection Schedule
  - Complete Overhaul

When is POD Required?

- Primary Agency Guidance is NASA STD-5009C, “Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components”
- Also called out in other Program specific requirements and procurement standards
  - SD73-SH-0082A Space Shuttle Orbiter Fracture Control Plan
  - SSP-30558 Fracture Control Requirements for Space Station
  - ANSI/AIAA S-080 – Metallic Pressure Vessels
  - ANSI/AIAA S-081 - COPV Metallic Pressure Vessel Liners
  - NASA-STD-5019 Fracture Control Requirements for Spaceflight Hardware
- Ultimately - NDE & Fracture Control technical authority for specific program or project

Certification of NDE Techniques NASA STD-5009C

- NASA fracture control requirements stipulate that all human-rated aerospace flight systems be subjected to fracture control procedures ***to preclude catastrophic failure***
- NASA-STD-5019A, Fracture Control Requirements for Spaceflight Hardware defines requirements for nondestructive evaluation.
- NASA-STD-5009C establishes the nondestructive evaluation (NDE) requirements for any NASA system or component, flight or ground, where fracture control and ***a quantitative demonstration of probability of detection (POD) are a requirement***