Technology Module: Technology Readiness Levels (TRLs)

Exploration Systems Engineering, version 1.0
Module Purpose: Technology Readiness

♦ Understand that technology has different levels of maturity and that lower maturity levels come with higher risks.

♦ Introduce the Technology Readiness Level (TRL) scale used to assess the maturity of technology for space flight.

♦ Demonstrate the correlation between technology readiness and risk.

♦ Describe how system risk can be reduced by early technology development of low TRL technologies.

♦ Use JWST as an example of a system using enabling technologies and early technology development to reduce project risks.
The Systems Engineer Considers New Technology for Space Missions

♦ In developing alternative system architectures, different performance and resource allocations are made.

♦ In some cases new technology is considered for a subsystem since it is necessary for success - it enables the mission.

♦ In other cases new technology is considered for a subsystem because it makes it easier on the other subsystems - it enhances the mission.

♦ In both cases, the systems engineer must balance the advantages and disadvantages of the alternatives to choose an implementation baseline.

♦ New technologies are always being developed with higher in-space performance. So the systems engineer must weigh the promise of new performance against the confidence of what has been done before.

♦ To include new technologies in a successful mission proposal, it is critical to allocate increased margin for properties such as cost, schedule and mass for the development of those technologies without violation of the resource limits.

♦ The technology readiness scale was developed to help systems engineers assess the risks associates with using new technology.
Introduction: Technology Readiness Levels

♦ The Technology Readiness Level (TRL) is a classification scale used to measure the maturity of a technology.
  • Describes the state-of-the-art of a given technology
  • Provides a “baseline” from which to advance (ultimately to flight)

♦ TRLs range from 1 - basic technology research to 9 - demonstrated operational capability in space.

♦ Typically, a TRL of 6 - technology demonstrated in a relevant environment - is required for a flight project development to be approved for implementation.

♦ TRLs indicate the inherent development risk.
  • A TRL of 1 or 2 represents a situation of relatively high risk
  • TRLs of 3-5 represent moderate risks
  • TRLs of 6-9 represent low risks
Technology Readiness Level (TRL) is a measure used to assess the maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating that technology into a system or subsystem.
Technology Readiness Levels

Declining TRL = determining what was demonstrated and under what conditions.
**Lower TRL Technology Requires More Time and Money to Be Flight Ready**

*Risk can be translated into cost impact.*

<table>
<thead>
<tr>
<th>TRL</th>
<th>Description</th>
<th>Added Cost %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Basic principles/research observed and reported.</td>
<td>Unknown</td>
</tr>
<tr>
<td>2.</td>
<td>Technology concept and/or application formulated.</td>
<td>Unknown</td>
</tr>
<tr>
<td>3.</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept.</td>
<td>20-25%</td>
</tr>
<tr>
<td>4.</td>
<td>Component and/or breadboard validation in lab environment.</td>
<td>15-20%</td>
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<tr>
<td>5.</td>
<td>Component and/or breadboard validation in relevant environment.</td>
<td>10-15%</td>
</tr>
<tr>
<td>6.</td>
<td>System/subsystem model or prototype demonstration in a relevant environment. (ground or space)</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>7.</td>
<td>System prototype demonstration in an operational (space) environment.</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>8.</td>
<td>Actual system completed and qualified through test and demonstration. (“flight qualified”)</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>9.</td>
<td>Actual system proven through successful mission operations. (“flight proven”)</td>
<td>&lt;10%</td>
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</tbody>
</table>
**Technology Readiness Levels (1/4)**

<table>
<thead>
<tr>
<th>TRL</th>
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</thead>
<tbody>
<tr>
<td>1. Basic principles observed and reported.</td>
<td>This is the lowest “level” of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).</td>
</tr>
<tr>
<td>2. Technology concept and/or application formulated.</td>
<td>Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be ‘invented’ or identified. For example, following the observation of high critical temperature superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.</td>
</tr>
<tr>
<td>3. Analytical and experimental critical function and/or characteristic proof of concept.</td>
<td>At this step in the maturation process, active research and development (R&amp;D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute “proof-of-concept” validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.</td>
</tr>
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</table>
## Technology Readiness Levels (2/4)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>4. Component and/or bread-board validation in laboratory environment.</td>
<td>Following successful “proof-of-concept” work, basic technological elements must be integrated to establish that the “pieces” will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively “low-fidelity” compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new ‘fuzzy logic’ approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.</td>
</tr>
<tr>
<td>5. Component and/or bread-board validation in relevant environment.</td>
<td>At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a ‘simulated’ or somewhat realistic environment. From one to several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array ‘blanket’ that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.</td>
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</table>
## Technology Readiness Levels (3/4)

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<tr>
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<tr>
<td><strong>6. System / subsystem model or prototype demonstration in a relevant environment.</strong></td>
<td>A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system — which would go well beyond ad hoc, ‘patch-cord’ or discrete component level breadboarding — would be tested in a relevant environment. At this level, if the only ‘relevant environment’ is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&amp;D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station ‘pallet’. In this example, the reason space is the ‘relevant’ environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system — and the only way to validate the technology is in space.</td>
</tr>
<tr>
<td><strong>7. System prototype demonstration in an operational environment.</strong></td>
<td>TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&amp;D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.</td>
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### Technology Readiness Levels (4/4)

<table>
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<tr>
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<tr>
<td>8. Actual system completed and qualified through test and demonstration.</td>
<td>By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true ‘system development’ for most technology elements. Example: this would include DDT&amp;E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.</td>
</tr>
<tr>
<td>9. Actual system proven through successful mission operations.</td>
<td>By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last ‘bug fixing’ aspects of true ‘system development’. For example, small fixes/changes to address problems found following launch (through ‘30 days’ or some related date). This might include integration of new technology into an existing system (such operating a new artificial intelligence tool into operational mission control at JSC). This TRL does not include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9: such ‘technology’ upgrades would start over at the appropriate level in the TRL system.</td>
</tr>
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</table>
JWST is a Good Example of a Project With Enabling New Technologies

- NEAR INFRARED DETECTORS (NIR)
- SIDECAR ASIC
- MID INFRARED DETECTORS (MIR)
- MIRI CRYOCOOLER
- MICROSHUTTERS
- HEAT SWITCH
- SUNSHIELD MEMBRANE
- WAVEFRONT SENSING & CONTROL (WFS&C)
- PRIMARY MIRROR
- CRYOGENIC STABLE STRUCTURES
JWST Mirror Technology Example

- The challenge was to make the mirrors lightweight for launch, but nearly distortion-free for excellent image quality.
- As JWST needs a new kind of mirror to meet these requirements, NASA set out to research new ways to build mirrors for telescopes. The Advanced Mirror System Demonstrator (AMSD) program was a four-year partnership between NASA, the National Reconnaissance Office and the US Air Force to study ways to build lightweight mirrors. Based on the ASMD studies, two test mirrors were built and fully tested. One was made from beryllium by Ball Aerospace; the other was built by Kodak (now ITT) and was made from a special type of glass.
- A team of experts was chosen to test both of these mirrors, to determine how well they work, how much they cost and how easy (or difficult) it would be to build a full-size, 6.5-meter mirror. The experts recommended that beryllium mirror be selected for the James Webb Space Telescope, for several reasons, such as because beryllium holds its shape at cryogenic temperatures. Based on the experts team's recommendation, Northrop Grumman Space Technology (the company that is leading the effort to build JWST) selected a beryllium mirror.

828 kg  ~500 kg

1996 - TRL 2
2010 - TRL 6
20?? - TRL 9
**JWST Mirror Technology Development**

- **AMSD Phase 1 – 1999**
  - 5 vendors selected for studies
  - Down select to 4 mirror architectures

- **AMSD Phase 2 – 2000**
  - 3 vendors (Goodrich, Kodak, Ball)

- **Prime Contractor Selection 2003**
  - Ball (Beryllium) and ITT/Kodak (ULE-glass) proposed as options

- **Mirror Material/Technology Selection, September, 2003**
  - Beryllium chosen for technical reasons (cryogenic CTE, thermal conductance, issues with glass)
  - Schedule and Tinsley staffing identified as JWST risks

- **Process improvements and risk reduction 2004**
  - Process improvements via 6-Sigma Study and follow-on identified potential schedule savings
  - Engineering Development Unit (EDU) added as key risk mitigation demonstration device (2003) along with AMSD Phase 3 Process improvements

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**Manufacturing Time/Unit Area**

- HST (2.4 m) ≈ 1 year/m²
- SIRTF (0.9 m) ≈ 3 years/m²
- JWST (6.5 m) ≈ 1 month/m²

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**JWST Requirement**

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Preparing for Operations - The Objectives of Moving up the TRL Scale

♦ The specific objective of the Advanced Mirror System Demonstrator (AMSD) effort was to demonstrate processes to manufacture mirrors with the following functional capabilities:
  • Large aperture => structurally stable
  • Low areal-density => lightweight
  • Manufacturability to 20 nm rms => could be polished
  • Stable cryogenic optical performance
♦ These demonstrated features pushed the mirror technology to TRL 5.

♦ More recent activities focused on closing the gap between where AMSD fell short of demonstrating TRL-6 readiness relative to JWST requirements
  • Specifically, demonstration of mirror survival through exposure to launch-load testing of a full integrated Primary Mirror Segment Assembly (PMSA)
  • Will the mirror survive the launch and environmental test conditions?
The debate: Where does invention end and normal engineering begin?

To satisfy independent reviewers, JWST team had to use an Engineering Development Unit (EDU) for the launch load test.

EDU = leader test article to validate processes before performing on the flight unit. It has the same form, fit and function as the flight unit will.
Primary Mirror Segment Assembly (PMSA) Component Definition

Mirror Substrate focus of technological development
Mirror Required Technological Development
**TRL-6 Primary Mirror Segment Assembly**

**Completion Definition**

- Demonstrate that a representative lightweight beryllium mirror assembly can survive flight vibro-acoustic loads and that the resulting mirror surface distortions are consistent with optical error budget allocations.

**Milestones**

- Complete TRL6 Program Coordination Meeting with GSFC/NGST
- Initiate Titanium Flexure Fabrication
- Complete Uniform CCOS Grinding
- ESPI-1 Speckle Interferometer Calibration Complete at GSFC
- Delta Frame Shipment to BATC from Axsys or LA Gauge
- ESPI-1 Delivered to BATC from GSFC (GFP)
- Complete Hexapod Assembly and Test at BATC
- EDU Primary Mirror Substrate shipment to BATC from Tinsley
- Complete Assembly of the EDU PMSA at BATC
- Complete Vibration Test at BATC
- Complete Acoustic Test at BATC

<table>
<thead>
<tr>
<th>DATE</th>
<th>PLAN</th>
<th>COMPL.</th>
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<tbody>
<tr>
<td>10/25/05</td>
<td>10/25/05</td>
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<tr>
<td>11/18/05</td>
<td>11/10/05</td>
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<td>6/13/06</td>
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<tr>
<td>6/19/06</td>
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</table>

**CURRENT STATUS**

- Working CCOS anomaly at Tinsley, expect to resume CCOS operations 12/9/05
- Conducting a trade of using first flight mirror out of Axsys for TRL-6 demo instead of EDU
  - Either can meet TRL-6 objectives
  - Recommendation to be made week of 12/15
- Delta Frame machining initiated at Axsys and LA Gauge

**Inch Stone Progress**

- Plan: 0 1 6 11 11 13 14 16 19 19 19 19 19 19 19 19
- Actual: 0 3 7

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*Exploration Systems Engineering: Technology Module*
Mirror TRL-6 Load Testing

♦ TRL-6 vibro-acoustics testing completed in August
♦ Pre to post electronic speckle pattern interferometer (ESPI) measurement indicated changes were below measurement error
♦ Mirror saw loads (17.6 G’s in X, 16.3 G’s in Y, 8.5 G’s in Z – Sine Burst) that enveloped worst case flight loads in all three axes.

PMSA before integration on vibe table
## Requirements Traceability

<table>
<thead>
<tr>
<th>Level 1 Requirements</th>
<th>Level 2 Requirements</th>
<th>Mirror Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1-01: Science Spectral Range</td>
<td>MR-211: Optical Transmission</td>
<td>PMSA-110: Spectral Reflectance 0.6-28 µm</td>
</tr>
<tr>
<td>L1-04: Celestial Coverage</td>
<td>MR-115: EE Stability</td>
<td>PMSA-170: Thermal Change &lt; 0.3 nm rms/K</td>
</tr>
<tr>
<td>L1-12: L2 Orbit</td>
<td>MR-099: Mass</td>
<td>PMSA-410: Mass &lt; 39.17 kg</td>
</tr>
<tr>
<td></td>
<td>MR-283: Launch Loads</td>
<td>PMSA-180: Launch Distortion &lt; 2.9 nm rms</td>
</tr>
<tr>
<td>L1-13: PM Collecting Area</td>
<td>MR-198: PM Collecting Area</td>
<td>PMSA-70: Polished Surface Area &gt; 1.46 m²</td>
</tr>
<tr>
<td>L1-14: Observatory Strehl Ratio</td>
<td>MR-228: Optical Telescope Element (OTE) Wave Front Error (WFE)</td>
<td>PMSA-150: Uncorrectable Fig &lt; 23.7 nm rms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PMSA-195: Creep &lt; 1.8 nm rms</td>
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**nm rms = nanometer root mean square**

The root mean square (rms) of the surface departure or wave-front deformation is an important value to extract from an optical test. The rms may be a tolerance that an optical fabricator is trying to meet, or it may be a parameter used by an optical designer to evaluate optical performance.
Four Primary Mirror Segment Assembly Technology Demonstrators Were Used to Show TRL-6

<table>
<thead>
<tr>
<th>Technology Demonstrator</th>
<th>Technology Developed</th>
<th>Validity to JWST</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBMD</td>
<td>Cryogenic Coating</td>
<td>SBMD developed a low stress gold coating application that can be applied to any beryllium mirror. Coating of large mirrors (like JWST) is not material specific and has been developed on other flight programs.</td>
</tr>
<tr>
<td>AMSD Mirror</td>
<td>Figuring, cryogenic performance, actuation capability</td>
<td>All differences between the JWST PMSA and the AMSD mirror improves manufacturability, cryogenic performance, and provides more actuation degrees of freedom.</td>
</tr>
<tr>
<td>AMSD Stress Coupons</td>
<td>Long term material stability</td>
<td>JWST PMSA’s are manufactured using the exact processing developed on AMSD III to assure low residual surface stresses and low material creep.</td>
</tr>
<tr>
<td>JWST Flight Segment</td>
<td>Low Launch distortion Actuation Capability</td>
<td>JWST flight segment used to show technology readiness</td>
</tr>
</tbody>
</table>
## Success Criteria and Results Summary

<table>
<thead>
<tr>
<th>PMSA Technology</th>
<th>Success Criteria</th>
<th>Basis for TRL-6 Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMSA-110: Spectral Reflectance 0.6-28 µm</strong></td>
<td>Gold Coating on O-30 w/28K survival</td>
<td>SBMD Gold Coating on O-30 w/28K survival demonstrated (and previous systems)</td>
</tr>
<tr>
<td><strong>PMSA-530: Operational Temperature 28-50K</strong></td>
<td>Demonstrated operation</td>
<td>AMSD XRCF cryogenic operation demonstrated</td>
</tr>
<tr>
<td><strong>PMSA-170: Thermal Change ≤ 0.3 nm rms/K</strong></td>
<td>≤ 7.5 nm rms 30-55K</td>
<td>AMSD XRCF cryogenic measured ≤ 7 nm rms 30-55 (Key Demonstration)</td>
</tr>
<tr>
<td><strong>PMSA-410: Mass ≤ 39.17 kg</strong></td>
<td>≤ 26.5 kg/m2</td>
<td>JWST TRL-6 B1 as-build areal density ≤ 26.1 kg/m2</td>
</tr>
<tr>
<td><strong>PMSA-180: Launch Distortion ≤ 2.9 nm rms</strong></td>
<td>≤ 14 nm rms measured ≤ 2.9 nm rms calculated</td>
<td>JWST TRL-6 B1 demonstrated 10.6 nm rms from Launch Loads (Within Measurement Error) and ≤ 2.9 via analysis</td>
</tr>
<tr>
<td><strong>PMSA-70: Polished Surface Area &gt; 1.46 m²</strong></td>
<td>1.5 m² Segment delivered from AXSYS</td>
<td>AMSD 20 nm-rms polishing convergence demonstration extrapolated 20% to JWST surface area</td>
</tr>
<tr>
<td><strong>PMSA-150: Uncorrectable Fig &lt; 23.7 nm rms</strong></td>
<td>≤ 23.7 nm rms Surface Error</td>
<td>AMSD 20 nm-rms polishing convergence demonstration</td>
</tr>
<tr>
<td><strong>PMSA-195: Creep ≤ 1.8 nm rms</strong></td>
<td>Design to O-30 Precision Elastic Limit (PEL)</td>
<td>AMSD experiment data and JWST process validation data incorporated to ensure ≤ 1500 psi residual stress</td>
</tr>
</tbody>
</table>
Module Summary: Technology Readiness

♦ The Technology Readiness Level (TRL) scale is used to assign maturity levels to technology considered for space flight.

♦ Low TRLs, or low technology maturity, correlate with development risk.

♦ Early development of enabling, low maturity technologies can reduce the development risk of a system.

♦ JWST has attempted to reduce the system development risk by developing some low maturity technologies before PDR, like the primary mirror segments.
Backup Slides
for Technology Module
**Technology Development for Orion**

**AR&D Sensors:** Characterizing optical and laser sensors that measure the range and orientation of a target vehicle during autonomous rendezvous and docking.

**Ablative TPS:** Qualifying thermal protection system materials in arcjet tests and developing a prototype heat shield.

**Structures & Materials:** Developing lightweight, high-strength parachute materials.

**Thermal Control:** Developing prototype flash evaporator, sublimator, and composite radiator for thermal control during different phases of mission.

**Exploration Life Support:** Developing a prototype carbon dioxide and moisture removal system.
Exploration website with videos of various tests, e.g., Orion parachutes, airbags.

Since the inception of the James Webb Space Telescope (JWST) program, to achieve its Level 1 Science Objectives, 6-8 meter class segmented primary mirror was required that could operate at ≤ 50K with 2 micrometers diffraction limited performance.

Such a mirror was a fundamental enabling technology that had never before been demonstrated – and did not exist.

- **AMSD Phase 1 – 1999**
  - 5 Vendors selected for studies
  - Down select to 4 mirror architectures

- **AMSD Phase 2 – 2000**
  - 3 vendors (Goodrich, Kodak, Ball)

- **Prime Contractor Selection 2003**
  - Ball (Beryllium) and ITT/Kodak (ULE) proposed as options

- **Mirror Material/Technology Selection, Sept 2003**
  - Beryllium chosen for technical reasons (cryogenic CTE, thermal conductance, issued with glass)

- **Process improvements\ Risk Reduction 2004**
  - Process improvements via 6-Sigma Study and follow-on identified potential schedule savings
  - EDU added as key risk mitigation demonstration device along with AMSD Phase 3 Process improvements (coupon and .5 meter demonstrations)

- **Most recent activities focused on closing the gap between where AMSD fell short of demonstrating TRL-6 readiness relative to JWST requirements**
  - Specifically, demonstration of mirror survival through exposure to launch-load testing of a full integrated Primary Mirror Segment Assembly (PMSA)
**Primary Mirror - NASA Review Team**

♦ NASA Review Team Assessment

TRL-6 success criteria met.
- The success of the primary mirror technology program is demonstrated by the fact that environmentally qualified flight mirror segments are now in production at a state-of-the-art manufacturing facility.

♦ Residual Risk/Comments

- Implications of the new (+/-150 microns) ROC requirements on the Mirror fabrication process and schedule needs evaluation. (Answered after T-NAR via telecon; 150 micron ROC requirement to be satisfied by cryo figure post XRCF.)
- Determine the optical performance implications of not meeting new ROC requirements. (Answered in same telecon; ROC optical figure error accounted for in error budget.)
- (Comment) The remaining risks are significant, but are limited to those inherent in any large optics manufacturing and testing task.
Pause to view James Webb Space Telescope (JWST) townhall status from Jan, 2008 (JWST_Townhall.pdf)

See page 3 for telescope deployed configuration
See pages 7-10 for mirror progress & photos of finishing process