Comprehensive Risk Assessment for Advanced Space Exploration

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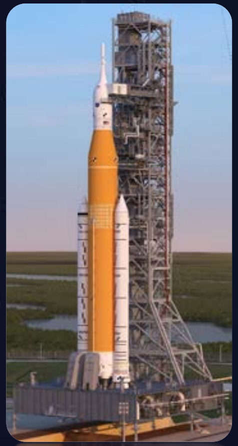
Flagship Missions/Programs

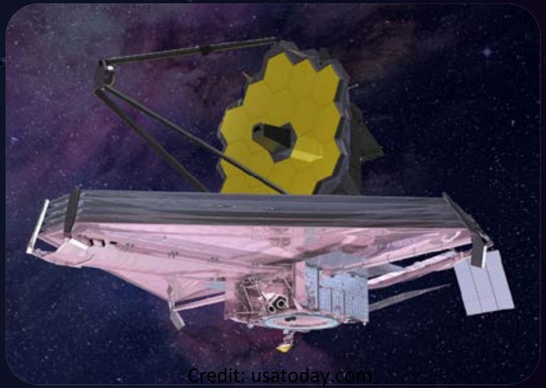
- Present state of missions demonstrating new technologies commonly run over budget and behind schedule
    - Production issues as well as project planning not fully encompassing of a project's unique attributes



- Space Launch System

Credit: parabolicarc.com

    - 10 year program with first launch in 2021



Credit: usatoday.com

- James Webb Space Telescope
    - $500-800 million launching in 2007
    - $9.66 billion- launching in 2021

National Aeronautics and Space Administration
www.nasa.gov

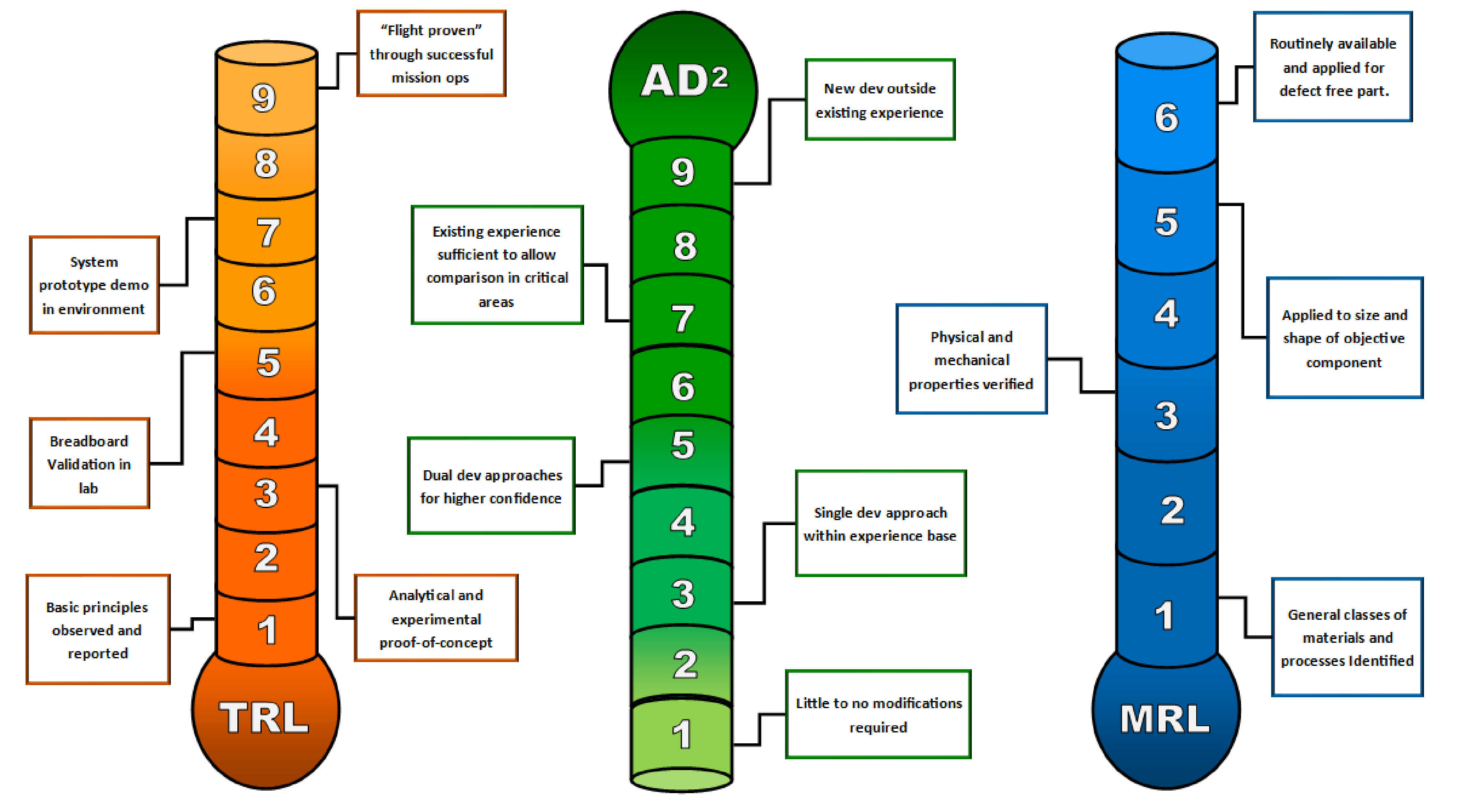
CRA Strategy

- Component-based readiness level reviews of systems and assemblies
- Flight and procurement heritage evaluations.
- Independent “non-biased” assessment TRL assessments
- Qualification by similarity acceptable.

ADVANCED CONCEPTS

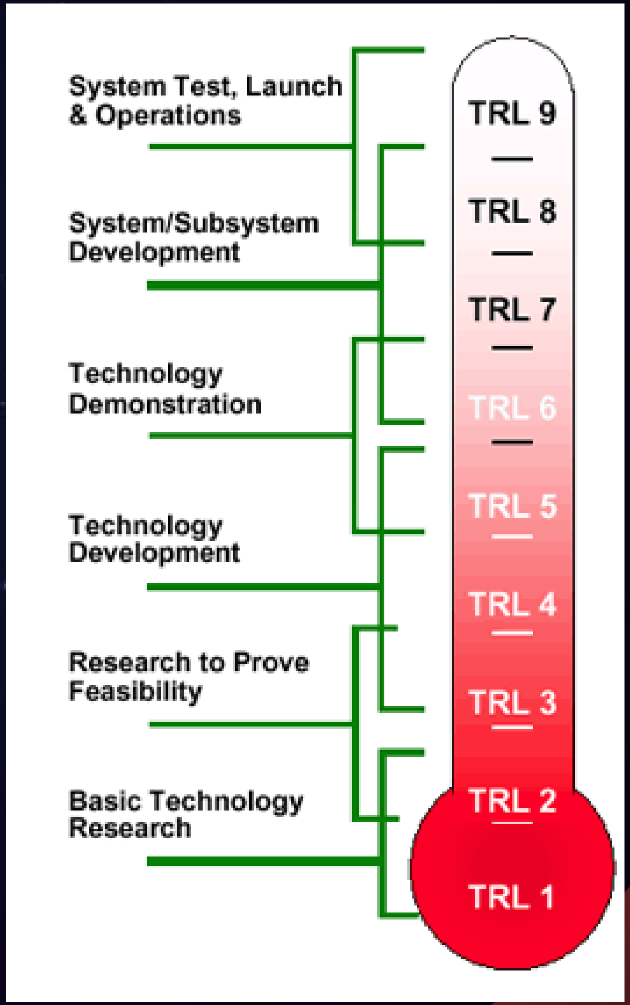
Ground Rules and Assumptions

- Assessments based on Technology Readiness Level (TRL), Advanced Degree of Difficulty (AD2), and Manufacturing Readiness Level (MRL).



Technology Readiness level

- Method for estimating flight maturity of technologies developed by NASA in the 1970s



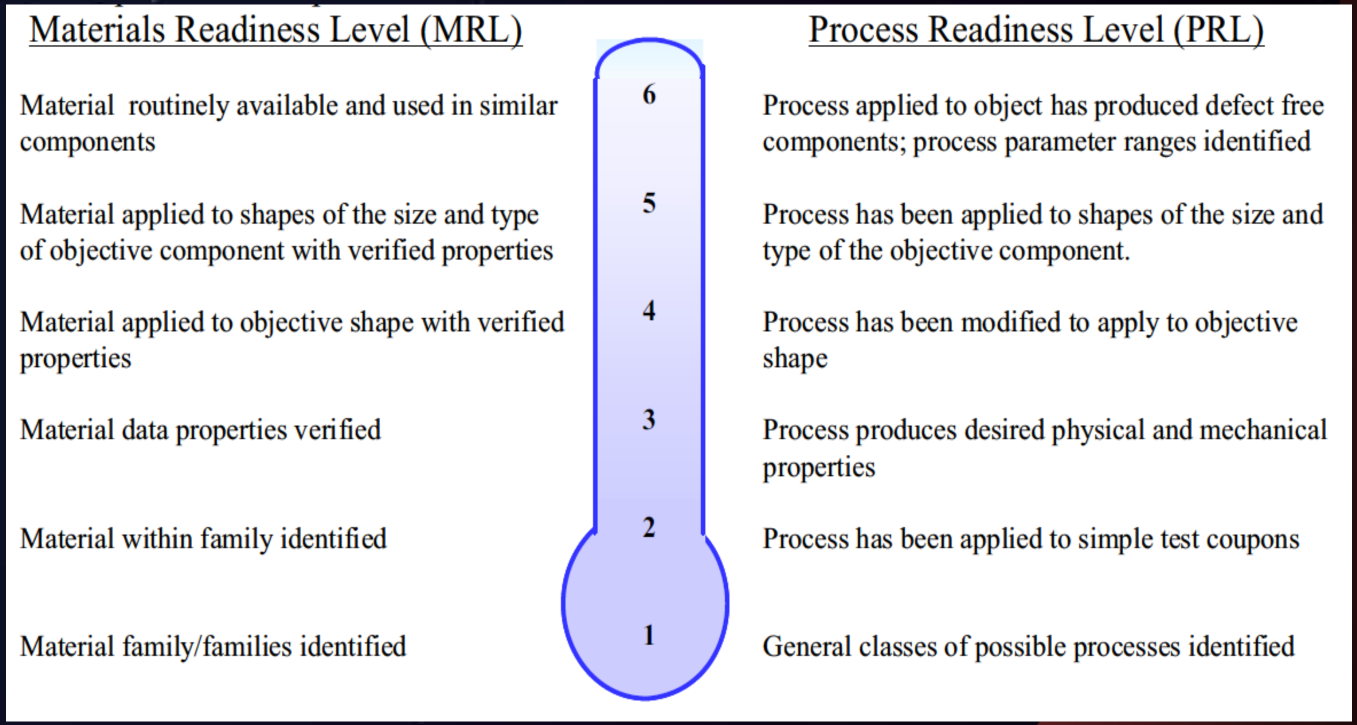
Advanced Degree of Difficulty

- Designed to determine the amount of systematic forward work required to raise a technology between readiness levels.
- Grounded in availability of relevant experience base.

AD_2	Definition	Risk	Category	Success Chance
1	Exists with no or only minor modifications being required. A single development approach is adequate.	0%	Well Understood (Variation)	Guaranteed Success
2	Exists but requires major modifications. A single development approach is adequate.	10%	Well Understood (Variation)	Almost Certain Success
3	Requires new development well within the experience base. A single development approach is adequate.	20%	Well Understood (Variation)	Almost Certain Success
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%	Well Understood (Variation)	Almost Certain Success
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%	Known Unknowns	Probably Will Succeed
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. Desired performance can be achieved in subsequent block upgrades with high confidence.	50%	Known Unknowns	Probably Will Succeed
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%	Known Unknowns	High Likelihood of Failure (High Reward)
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be prepared.	80%	Unknown Unknowns	High Likelihood of Failure (High Reward)
9	**Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.**	**100%**	**Chaos**	**Almost Certain Failure (Very High Reward)**

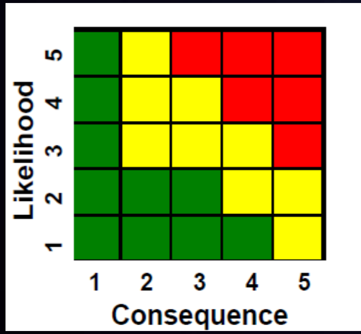
Manufacturing Readiness Level

- Developed to assess the maturity of relevant materials and processes required for projects



Risk level/ Classes

- As defined in NASA IV&V Doc S3001
  - Measure of the potential inability to achieve a goal or target within defined safety, cost, schedule, and technical constraint
  - 2 components: the likelihood of and the consequence of failing
  - Internal or external
- Identification and clear definition of risks to a mission or project are integral to ensuring success

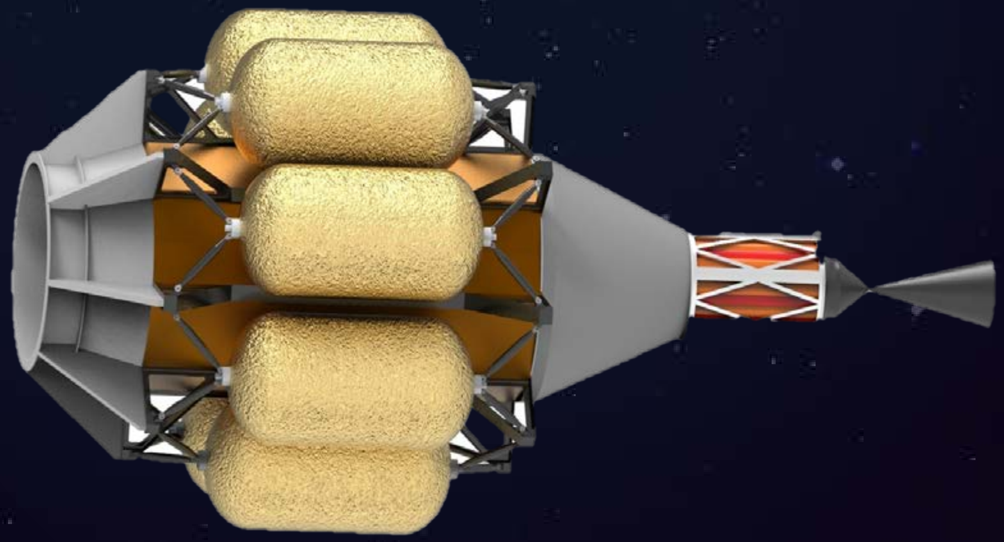


Risk Class	Posture	Detail
Class A	Lowest Risk Posture	Failure would have extreme consequences to public safety or priority national science objectives.
Class B	Low Risk Posture	High priority national asset whose loss would be impactful to public safety or national science objectives
Class C	Moderate Risk Posture	An instrument or spacecraft whose loss would result in a loss or delay of some key national science objectives
Class D	Cost/ Schedule are greater or equal to mission success	May credible mission failure mechanism may exist. Technical risk is medium by design.

ADVANCED CONCEPTS

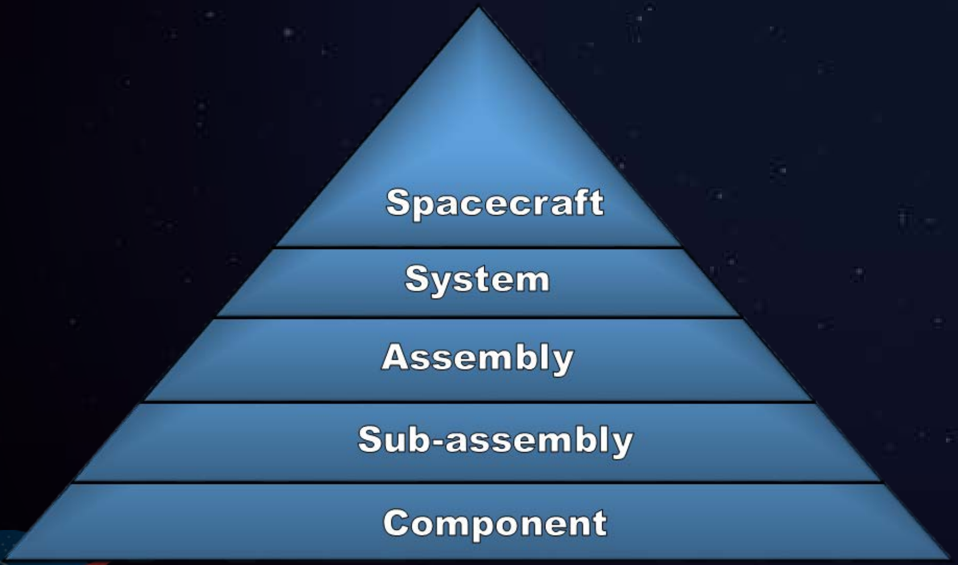
NTP FD1

- Proof of concept mission jointly completed by NASA and the DOE
- Design utilizes simplistic spacecraft and main propulsion system for completion by 2024.
- No navigation and simple on/off of main propulsion system



System list

- Systems identified through standard Advanced Concepts Office practices
- General Functional requirements determined based on customer inputs and mission goals
    - Provide foundation for required components

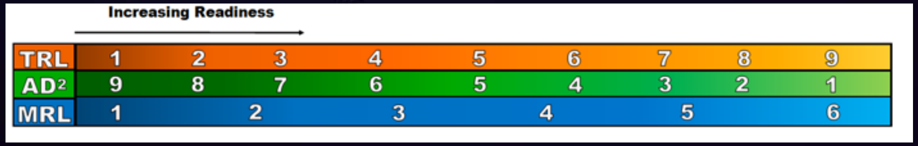


Discipline/Owner	Functional Requirements
On-Board Propulsion (OBP)	• Provides propulsion capability for primary propulsive maneuvers (e.g. current required DV for Venus fly-by trajectory) • Provides s/c attitude control system (ACS) for mission duration
Power	• Provides conditioned power to all spacecraft elements during all mission phases
Structures	• Assure structural integrity (sizing per NASA-STD5001B) based on all aspects of spacecraft design • Assure launch load compatibility with requirements from applicable Payload Users Guide
Thermal Management	• Assure required thermal environment for all spacecraft systems (e.g. thermal protection from nuclear and solar heat loads environments; required waste heat rejection to space)
Spacecraft Avionics (Non-Nuclear)	• Provides s/c Command & Data Handling (C&DH), Guidance, Navigation, & Control (GN&C), Instrumentation, and Communications. • NTP-MPS will have independent instrumentation from spacecraft avionics.
Instrumentation (Nuclear)	• Provide feedback on reactor health and operating conditions
Propulsion (Main)	• Provide GH2 storage regulated flow and nozzle expansion for thrust
Reactor	• Provide controlled nuclear source for GH2 propellant and flow path from plenum to nozzle chamber inlet

Onboard Propulsion Component List

- List of major components (excluding valves) with individual functional requirements
- Indications of procurement strategy and the necessity for additional development for component application
- Discipline leads provide initial recommendations for readiness levels and representative parts

Component	Functional Requirement	Quantity	Make / Buy	TRL	AD^2	MRL	Representative Part/ Analog	Notes
TCM Thruster (100-lbf MON3/Hydrazine)	Provide translational thrust	4	Purchase - COTS	9	1	6	AR HiPAT Dual Mode	Anticipated Burns: <10
ACS Thruster (5-lbf Hydrazine)	Provide rotational thrust	12	Purchase - COTS	9	1	6	AR MR-106E	Anticipated Burns: <1000
Oxidizer Tank (Titanium, 0.10 m^3)	Store NTO (MON-3)	1	Purchase - COTS w/ Development	7	1	6	NGIS 80387-1	Custom tanks directly adapted from existing bounding technology
Fuel Tank (Titanium, 0.40 m^3)	Store Hydrazine	1	Purchase - COTS w/ Development	7	1	6	NGIS 80398-1	Custom tanks directly adapted from existing bounding technology
Pressurant Tank (Aluminum COPV, 0.11 m^3)	Store Helium	1	Purchase - COTS w/ Development	7	1	6	NGIS 80584-1	Custom tanks directly adapted from existing bounding technology
Propellant Filter	Filter particulates from liquid propellant	2	Purchase - COTS	9	1	6	Vacco 14241-589	4 TCM engines flow 141 g/sec each
Pressurant Filter	Filter particulates from gaseous pressurant	1	Purchase - COTS	9	1	6	Vacco 14288-633	Direct purchase - no development



ADVANCED CONCEPTS

Onboard Propulsion Heritage List

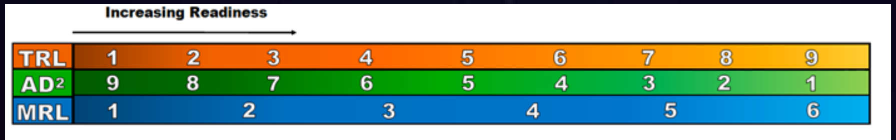
- Evaluation of component procurement and flight heritage to prove ease of access and reliability
- Identifying multiple suppliers to reduce single point failures in procurement strategy

Component	Potential Suppliers	Representative Part(s)	Sample Flight Heritage
TCM Thruster (100-lbf MON3/Hydrazine)	Aerojet Rocketdyne, NGIS, IHI et al.	AR HiPAT Dual Mode, IHI BT-4	Chandra X-Ray Observatory (NGIS), Cygnus Service Module (IHI)
ACS Thruster (5-lbf Hydrazine)	Aerojet Rocketdyne, NGIS, et al.	AR MR-106E, NGIS MRE 4.0	Mars Odyssey, Cygnus (106M variant), Gamma Ray Observatory, various launch vehicles, et al.
Oxidizer Tank (Titanium, 0.10 m^3)	NGIS, Rafael, et al.	NGIS 80387-1	Earth Space satellites and interplanetary probes
Fuel Tank (Titanium, 0.40 m^3)	NGIS, Rafael, et al.	NGIS 80398-1	Earth Space satellites and interplanetary probes
Pressurant Tank (Aluminum COPV, 0.11 m^3)	NGIS, ARDE, General Dynamics, et al.	NGIS 80584-1	Earth Space satellites and interplanetary probes
Propellant Filter	Vacco, Moog, et al.	Vacco 14241-589	Earth Space satellites and interplanetary probes
Pressurant Filter	Vacco, Moog, et al.	Vacco 14288-633	Earth Space satellites and interplanetary probes

Reactor Sub-assembly List

- Complexity of new technologies being implemented in the FD1 propulsion system, reactor was broken down into assemblies for evaluation

Assembly	Functional Requirement	Quantity	Make / Buy	TRL	AD^2	MRL	Notes
Reactor Fuel Assembly	• Generate power and transfer heat to propellant	1	Specified Procurement with in-house assembly	5	4	5	U-Mo monolithic fuel welded to coolant circulation tubing and the inlet/outlet plena. Housed in steel reactor vessel along with axial reflectors
Reflector Assembly	• Provide reactor control • Thermal heat rejection during startup and steady state operation	1	Specified Procurement with in-house assembly	6	3	5	Radial Be-Metal Reflector housing for six control drums made of Be and B4C. Gears, bearings and structural supports.
Shield Assembly	• Provide neutron and gamma-ray shielding • Prevent H_2 heat-up during startup	1	Specified Procurement with in-house assembly	6	4	4	Validated design principles-dependent on shielding strategy requires design-specific development
Instrumentation Assembly	• Provide reactor data collection used for analysis and control	1	Specified Procurement with in-house assembly	6	4	6	Temperature, pressure, structural stress/strain, neutron flux, neutron period
Control Assembly	• Provide reactor control during startup and shutdown.	1	Specified Procurement with in-house assembly	5	4	6	Step motors, digital motor controllers, power, wiring, position indicators



ADVANCED CONCEPTS

Reactor Instrumentation and M/C

- Addition of mission criticality criteria to separate non-critical systems from those that are required for mission success.
- Delineating reactor health instrumentation from nonessential instrumentation

Component	Functional Requirement	QTY	Make / Buy	TRL	AD^2	MRL	Representative Part/ Analog	M/C	Notes
Optical Video Camera - Plume	Monitor health of the NTP by observing the optical properties of the plume	1	Modify Existing Unit	6	3	6	Ahlberg Z160 HD Camera	No	20MRad total dose, 1MRad/Hr, 720x1280p
Spectrometer w/MEB - Plume	Monitor health of the NTP by observing the spectral properties of the plume	1	Modify Existing Unit	7	2	6	OSIRIS-Rex OVIRS	No	Spectrometer with Electronics Unit, Est size
IR Video Camera - Reactor	Monitor health and temperature of the reactor by observing Infrared emissions	2	Modify Existing Unit	7	2	6	Malin Space System ECAM-IR1	No	384x288p, 330g + 10 kg for radiation housing (ref SeaFLIR230 18kg)
Thermocouple	Monitor health and temperature of the reactor	50	Procure Existing Unit	9	1	6	Omega/other	Yes	Used extensively in KRUSTY in relevant environment. Needed operational life < week.
Radiation Detector Camera -Reactor	Monitor health and state of the reactor by observing radiation emissions	2	Modify Existing Unit	6	3	6	RMD Inc. RadCam,	No	640x480p, 35 degree FOV. Ref ThermoFisher RHRDP mass, Estimated power
Neutron Detector	Monitor state of the reactor by observing Neutron emissions	2	Modify Existing Unit	4	4	6	TBD	No	Ref Rolls-Royce Civil Nuclear Huntsville 423-756-9730
Neutron Detector Electronics Unit	Provide data processing of the Neutron detector	2	Modify Existing Unit	4	4	6	TBD	No	Ref Rolls-Royce Civil Nuclear Huntsville 423-756-9730
DVR Electronics Unit	Provide data processing and storage of optical camera	2	Modify Existing Unit	7	2	6	Malin Space System ECAM-DVR4	Yes	
Data Acquisition Unit	Collect and condition sensor data for data bus	4	Modify Existing Unit	6	3	6	Ampex AMux700	Yes	7 module + base, Commercial, not space rated.
Instrumentation and Wiring	Provide electrical and data connections between boxes sensors and actuators	TBD	Make	7	3	6	Used MER, ACO studies	Yes	Its known how to make space rated cabling. But at pre-phase A concept level its not known how many.

Increasing Readiness →

TRL	1	2	3	4	5	6	7	8	9
AD^2	9	8	7	6	5	4	3	2	1
MRL	1	2	3	4	5	6			

System Evaluation Results

- Completed lists of components and heritage inform final top-level evaluation with clarifying rationales for readiness level designations.

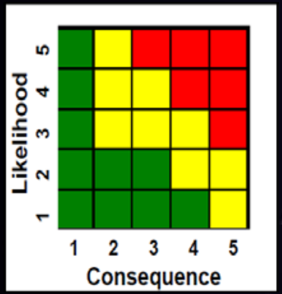
Discipline/Owner	Functional Requirements	System TRL	AD^2	MRL	Comments
On-Board Propulsion (OBP)	• Provides propulsion capability for primary propulsive maneuvers (e.g. current required DV for Venus fly-by trajectory) • Provides s/c attitude control system (ACS) for mission duration	7	1	6	• Both primary and ACS propulsion system components are commercial-off-the-shelf products. • FD1-specific developments (e.g. sized propellant tanks) will be straightforward adaptations of existing technology.
Power	• Provides conditioned power to all spacecraft elements during all mission phases	7	3	5	• Solar Arrays and Power Electronics require component development, but are standard assemblies commonly fabricated for space missions. • No technology development is required.
Structures	• Assure structural integrity (sizing per NASA-STD5001B) based on all aspects of spacecraft design • Assure launch load compatibility with requirements from applicable Payload Users Guide	7	1	6	• Factors of safety for Ultimate and Yield Strength required • First cantilever lateral and axial normal modes as specified in the Payload Users Guide for the launch vehicle chosen
Thermal Management	• Assure required thermal environment for all spacecraft systems (e.g. thermal protection from nuclear and solar heat loads environments; required waste heat rejection to space)	7	2	4	• Reliance on standard thermal management technologies with heritage from SWIFT, ISS, STS, Space Shuttle, and many commercial and DOD spacecraft
Spacecraft Avionics (Non-Nuclear)	• Provides s/c Command & Data Handling (C&DH), Guidance, Navigation, & Control (GN&C), Instrumentation, and Communications. • NTP-MPS will have independent instrumentation from spacecraft avionics.	7	2	6	• Separating Spacecraft and NTP propulsion system allows for high TRL on most spacecraft avionics, providing a cost effective, reliable, and safe platform from the NTP demonstration. • Space craft avionics system controls reactor operational profile and receives operational conditions
Instrumentation (Nuclear)	• Provide feedback on reactor health and operating conditions	5	3	6	• Assessment features determination of mission critical systems only. • Conservative estimation subject to SME review
Propulsion (Main)	• Provide GH2 storage regulated flow and nozzle expansion for thrust	7	1	6	• Standard Fabrication processes and components
Reactor	• Provide controlled nuclear source for GH2 propellant and flow path from plenum to nozzle chamber inlet	5	4	4	• Conservatism assumed in assessment pending design finalization and independent SME review

Increasing Readiness →

TRL	1	2	3	4	5	6	7	8	9
AD^2	9	8	7	6	5	4	3	2	1
MRL	1		2		3	4		5	6

Top-level Spacecraft Risks

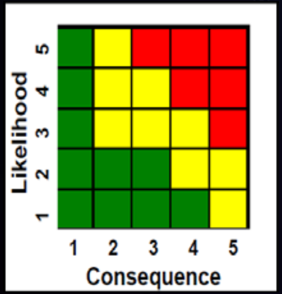
- Overarching risks that can be attributed to all systems of spacecraft



Risk #	Risk Title	Risk Statement	Risk Type	Risk Assessment			Mitigation Plan
				Likelihood	Consequence	Score	
NTP-1	**Component Delivery Issues**	Long procurement lead times incompatible with FY24 launch date leading to delay in project schedule.	S	2	4	8	1. FY19 RFI/thorough SME review 2. FY20 Procurement 3. Schedule incentive contracts 4. Full year of funded schedule reserve
NTP-2	**Sub-System Assembly and Test Issues**	End-to-end system assembly/testing delayed by component unavailability, facility issues, and/or NASA program issues resulting in schedule delays for the project.	S	2	4	8	1. FY19 RFI/thorough SME review 2. FY21 engineering model system test 3. Secure alternate facilities 4. Unambiguous NASA leadership with pre-PDR SME oversight
NTP-3	**Overestimation of Technology Heritage**	Component technology readiness assessment inaccurate due to loss of capability (e.g. NEA Scout N2 thruster) or out-of-specification FD1 requirement resulting in unaccounted for technology development, delaying the project schedule.	T	1	3	3	1. FY19 RFI/thorough SME review 2. FY20 Procurement 3. Alternate source 4. Funded schedule reserve
NTP-4	**Nuclear Compatibility Issues**	Inaccurate MRL assessment due to unknown radiation tolerance issues causing resulting in design rework of the reactor and/or spacecraft, delaying schedule and increasing costs.	T	1	3	3	1. FY19 SME review 2. Spacecraft design modifications to reduce line-of sight to acceptable value 3. Increased shielding (spacecraft and/or component-specific) 4. Possible mitigation through subscale material development testing

Reactor Associated Risks

- Generated list of risks based on SME discussions and independent reviews.
- Used in determining project risk posture and cost analysis



Risk #	Risk Title	Risk Statement	Risk Type	Risk Assessment			Mitigation Plan
				Likelihood	Consequence	Score	
RXR-1	**Component and Manufacturing Delivery Issues**	Procurement lead times incompatible with FY24 launch date	**S**	2	4	**8**	1. FY19 RFI/thorough SME review 2. FY20 Procurement 3. Schedule incentive contracts 4. Full year of funded schedule reserve
RXR-2	**Reactor System Assembly and Test Issues**	End-to-end System assembly/testing delayed by component unavailability, facility issues, and/or NASA program issues will require significant changes to schedule.	**S**	2	4	**8**	1. FY19 RFI/thorough SME review 2. FY21 engineering model system test 3. Secure alternate facilities 4. Unambiguous NASA leadership with pre-PDR SME oversight
RXR-3	**Launch Safety Non-Approval**	Design does not meet launch safety criteria and will have to be redesigned for additional critical design reviews at the cost of schedule	**S**	2	3	**6**	1. Pre-design safety analysis 2. Meeting with review team 3. Meeting with Approval committee 4. Ensuring identified functional requirements are met
RXR-4	**Inadequate Heat Transfer to Propellant**	Poor thermal conduction from fuel to flow channel will lead to insufficient propellant heating to achieve target Isp	**T**	2	3	**6**	1. Test series for subscale/single channel fuel element testing 2. Design validation through hardware testing
RXR-5	**Inability to Achieve Criticality**	Inability for reactor to produce sufficient will lead to insufficient propellant heating to achieve target Isp	**T**	1	5	**5**	1. Use of benchmarked codes 2. Zero Power Critical at DAF 3. Full model and test of CTE issues
RXR-6	**Drum/Actuator Failure**	Electrical Signal Failure, drum binding failure, or radiation environment failure may disable reactor or disable ability for reactor to achieve sub-criticality, will leave reactor in on state	**T**	1	3	**3**	1. Test series in a relevant environment(s) 2. Ground based testing is recommended 3. Design flexibility allows for drum failure if deemed necessary
RXR-7	**Reflector Cracks During Launch**	Inability for reactor to produce sufficient will lead to insufficient propellant heating to achieve target Isp	**T**	1	2	**2**	1. Vibration testing during qualification phase

ADVANCED CONCEPTS

Conclusion

- The CRA allows for extensive Pre-Phase A and Phase A project planning for missions encumbered by unfamiliar technologies in spaceflight and increasing complexity.
- Presents a centralized process utilizing
- Non-biased/ non-advocate reviews
- Component-level baseline readiness determination for system-level procurement strategies
- Procurement strategies with no single-point failures
- Fully-developed risk posture for cost analysis and project Risk class determination