AEROJET ROCKETDYNE
A GenCorp Company

Design-to-Cost and Robust Liquid Rocket Engine Design Using PMDA/PMDO and MBSE

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14 April 2015

Phx 2015 User Conference

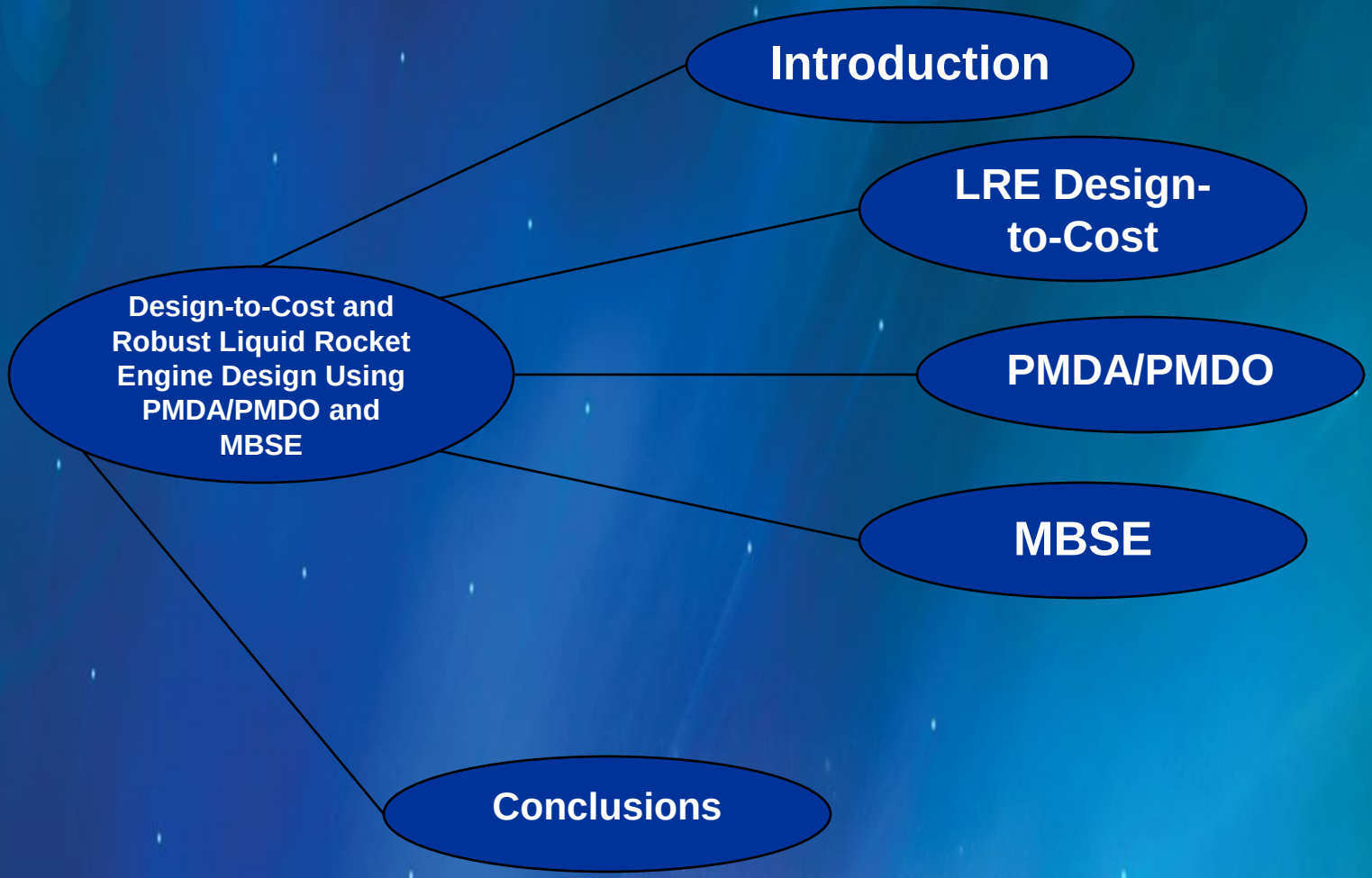
- **Today's presentation is philosophical and was presented at AIAA Space 2014**
  - **Matthew Long, Heidi Davidz, and James Horton. "Design-to-Cost and Robust Liquid Rocket Engine Design Using PMDA/PMDO and MBSE". *AIAA SPACE 2014 Conference and Exposition*, August 4-7 2014.**

- **Results of applying this methodology to a development program will be presented at AIAA JPC 2015**
  - **Application of multidisciplinary analysis and optimization on AR1 Using ModelCenter™**

AR1 Twin Booster Engine

Ref https://www.rocket.com/ar1-booster-engine
Retrieved 3/27/15

Outline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LRE Design-to-Cost
Design-to-Cost and Robust Liquid Rocket Engine Design Using PMDA/PMDO and MBSE
PMDA/PMDO
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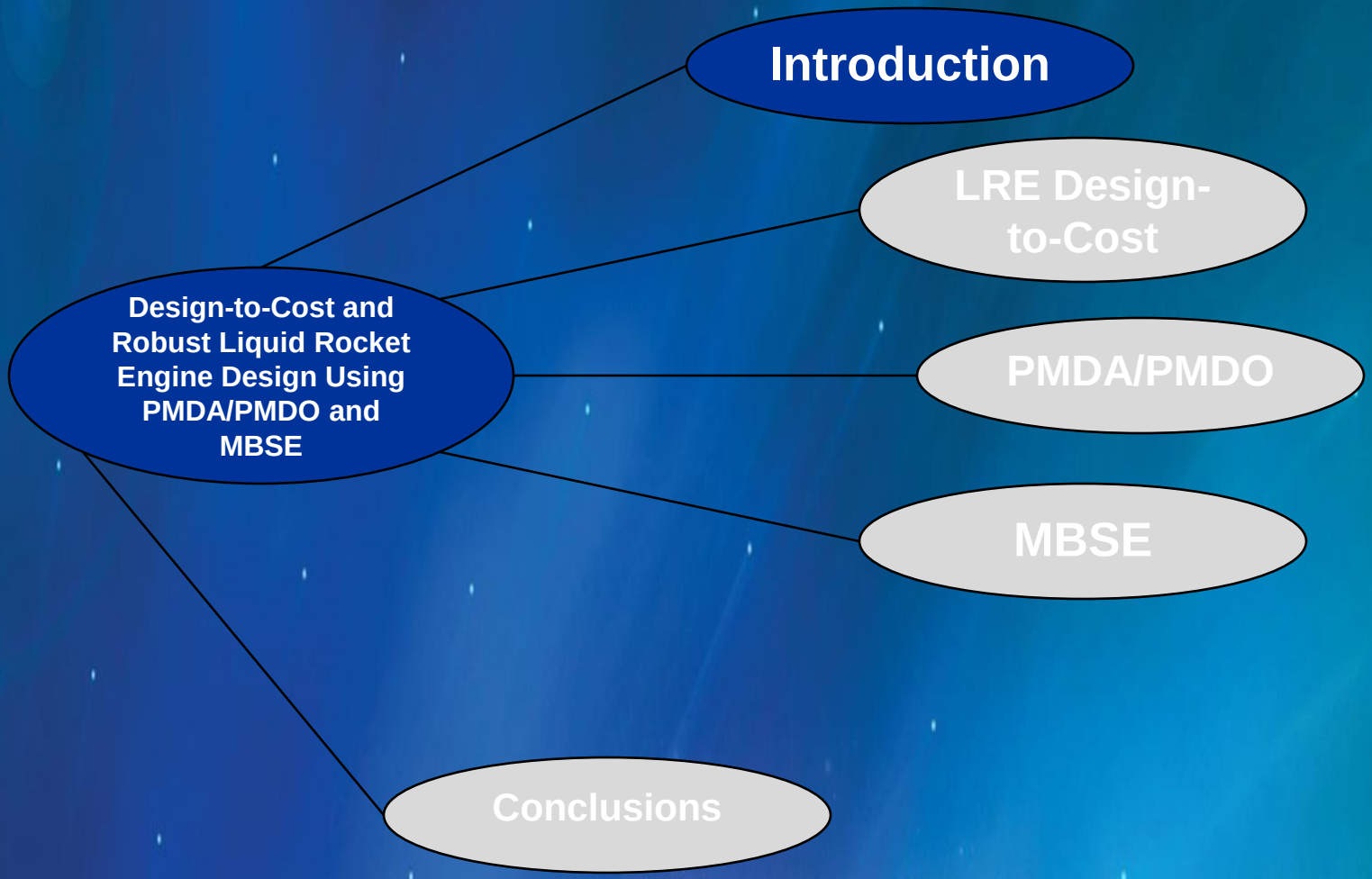
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Why PMDA/PMDO and MBSE?

"We can lick gravity, but sometimes the paperwork can be overwhelming!"

Wernher von Braun

Introduction

- Liquid Rocket Engine (LRE) must serve a useful purpose to perform a given mission
  - Modeling a vehicle mission involves the disciplines of
    - Orbital mechanics
    - Weights and sizing
    - Aerodynamics
    - Structural load analysis
    - Trajectory analysis.

Designing a LRE requires the disciplines

- Combustion
- Heat transfer
- Structures
- Turbomachinery design
- Fluid mechanics
- Material properties.

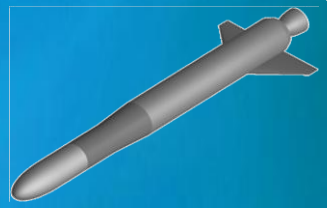
Engineers assess the LRE by:

Manufacturability
Transportation
Test
Cost
Safety
Reliability

- Managing LRE complexity is challenging

- Renewed emphasis on life cycle costs requires new approaches to manage LRE complexity

- PMDA/PMDO & MBSE can aid in realizing a LRE design-to-cost solution



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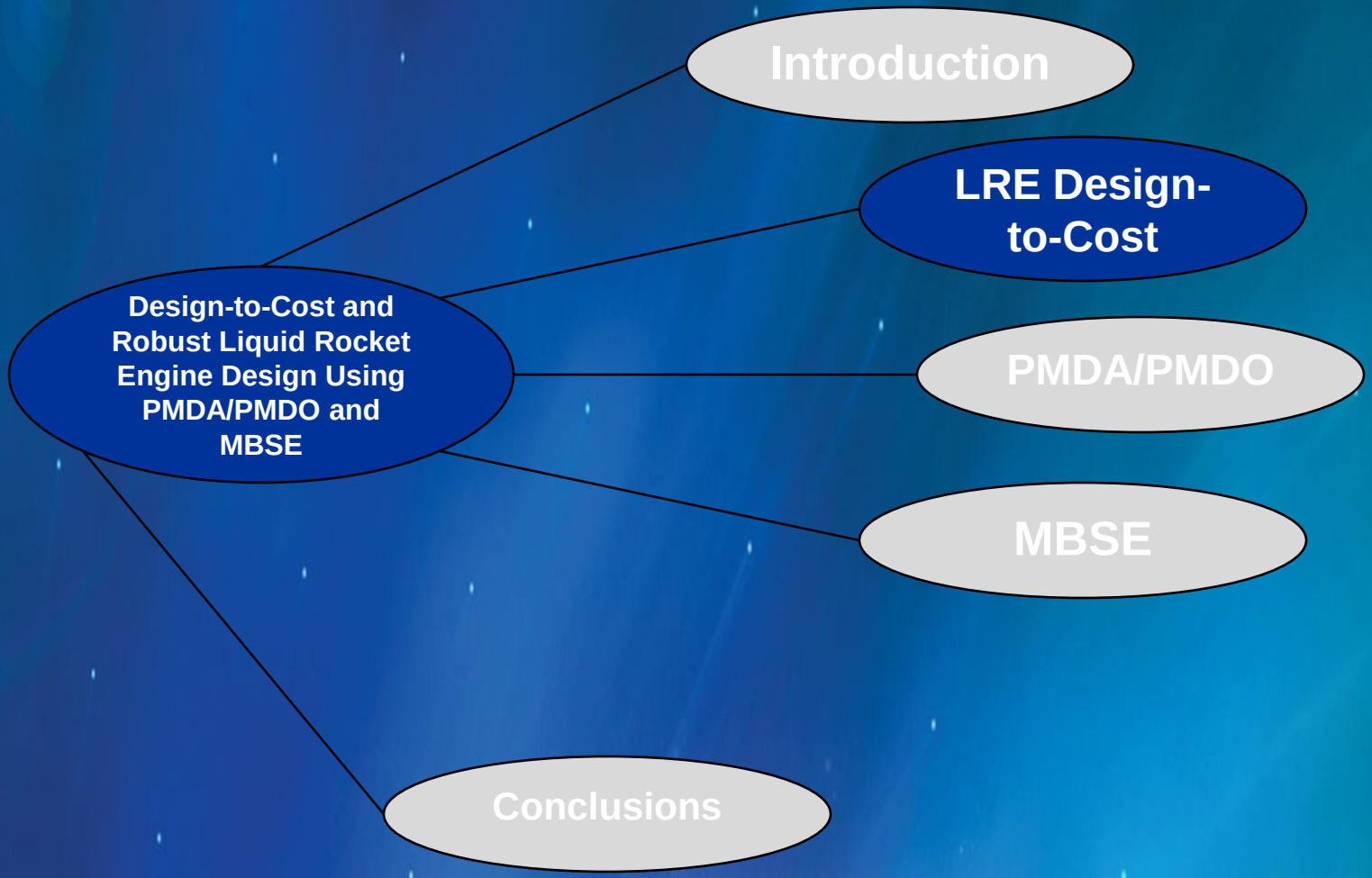
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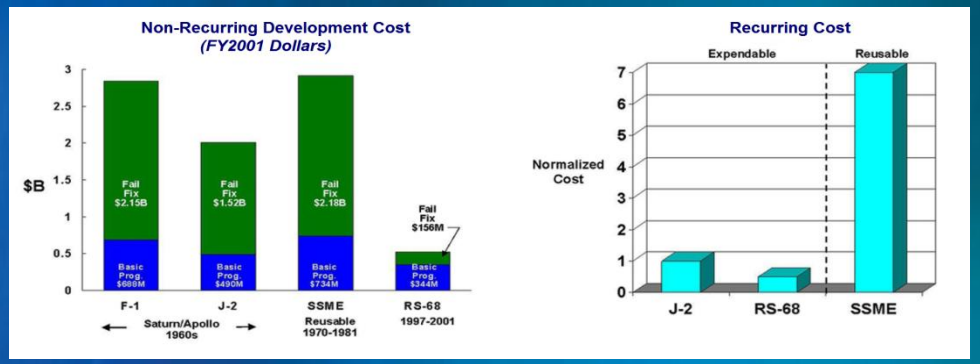
Liquid Rocket Engine Design-To-Cost

- Reduced costs of LRE has been sought for 40 years
- Maturity of LRE technologies requires re-examination of philosophy
- Shift emphasis from design-to-requirements/design to performance to design-to-cost / minimum life cycle costs
- Some Examples
  - EELV RS-68 – cost reduction
  - Realized in fail-fix costs
  - Improved Vulcain LRE (Vulcain 2)
  - Low cost carriers
    - SpaceX Falcon 9
    - Orbital Sciences Antares
    - JAXA Epsilon
    - Mitsubishi Heavy Industries' H-III
    - Astrium Ariane 6
    - Avio's Vega



Historical Engine Development and Recurring Costs at Rocketdyne

- Design-to-Cost philosophies require a solution that successfully navigates a complex multidisciplinary LRE design space

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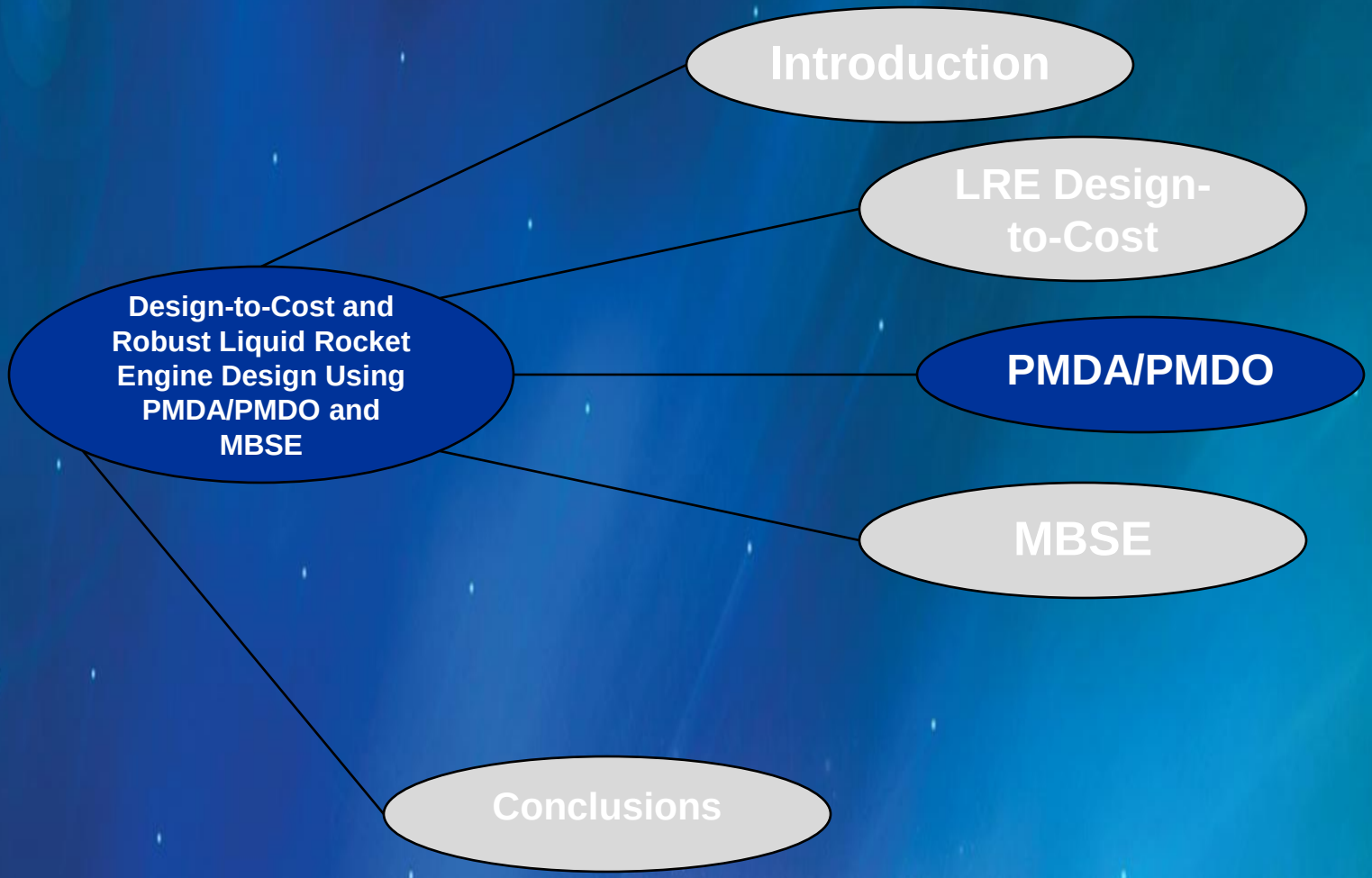
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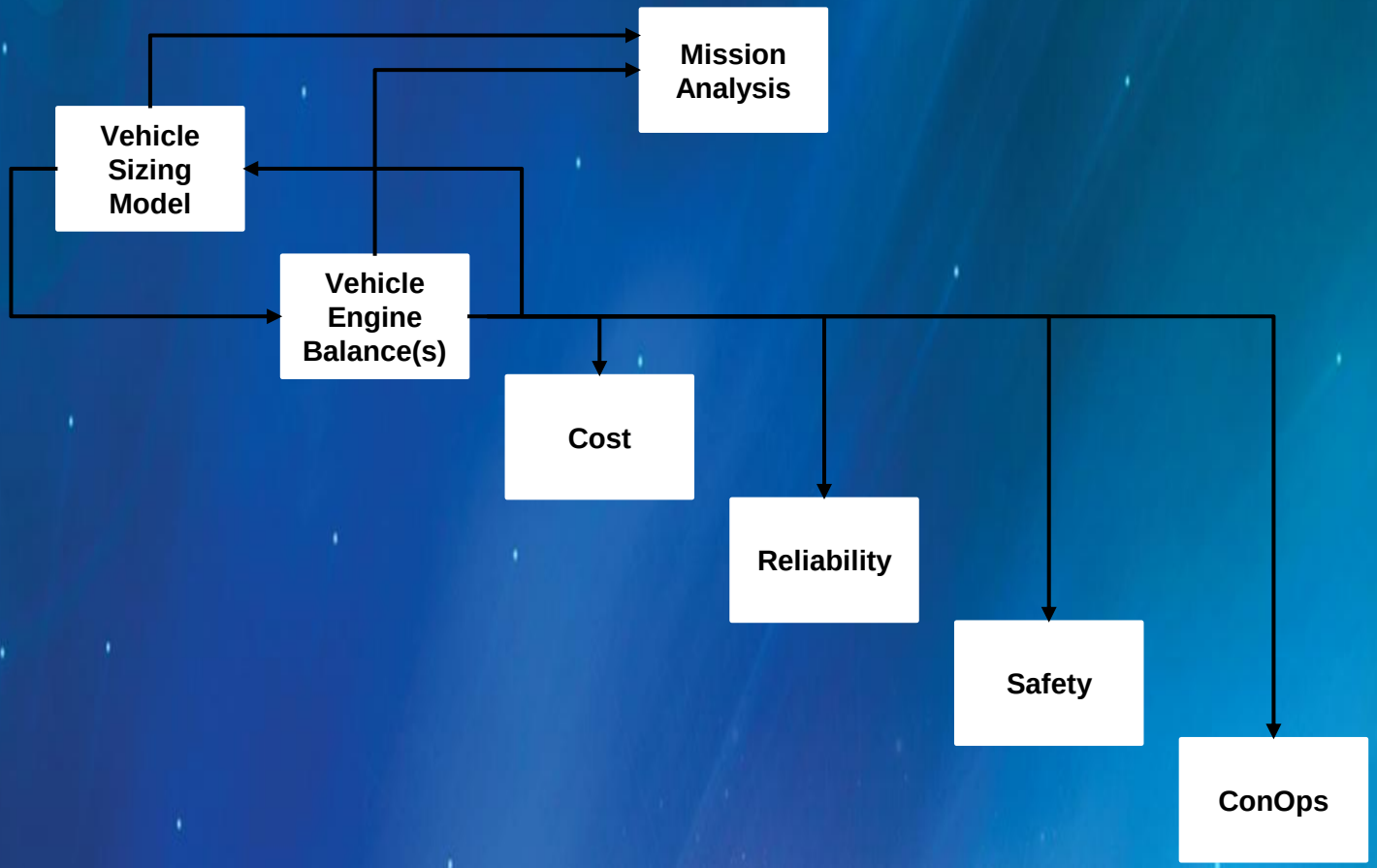
PMDA/PMDO

- Increases in computer power in 1970s and the advent of computer aided design and optimization altered the approach to engineering design.
- Industry shift in focus from performance driven designs to ones that minimized life cycle costs.
- Preliminary Multidisciplinary Analysis (PMDA) and Preliminary Multidisciplinary Optimization (PMDO) is an engineering philosophy that employs optimization methods to solve complex problems across several disciplines concurrently.
- The objective of PMDA/PMDO is to deliver a superior system solution by allowing for a deeper understanding of the interactions between the disciplines.
- Robustness comes at the price of increased complexity of the problem.

Notional Vehicle System Architecture Model for PMDA/PMDO



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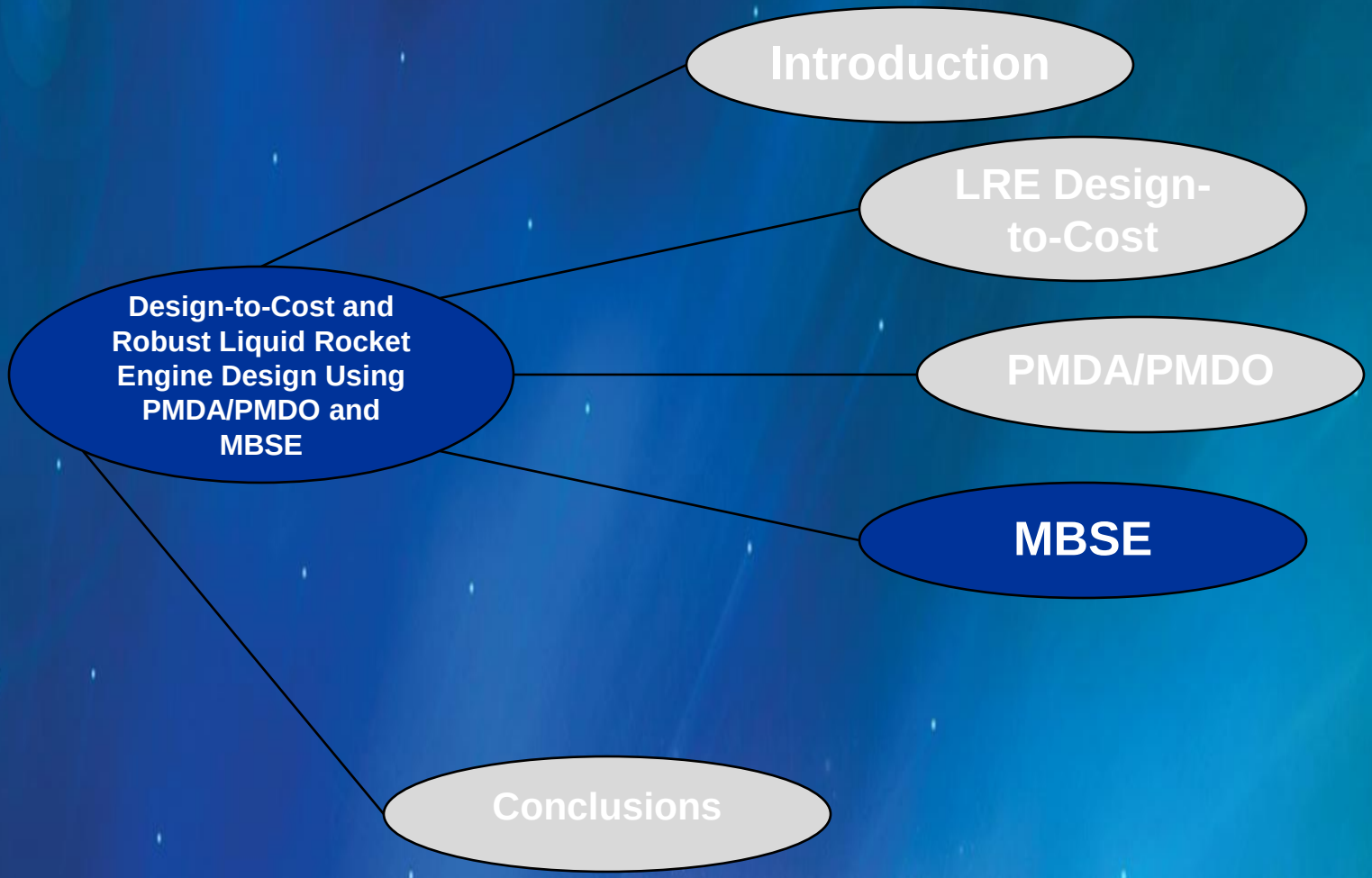
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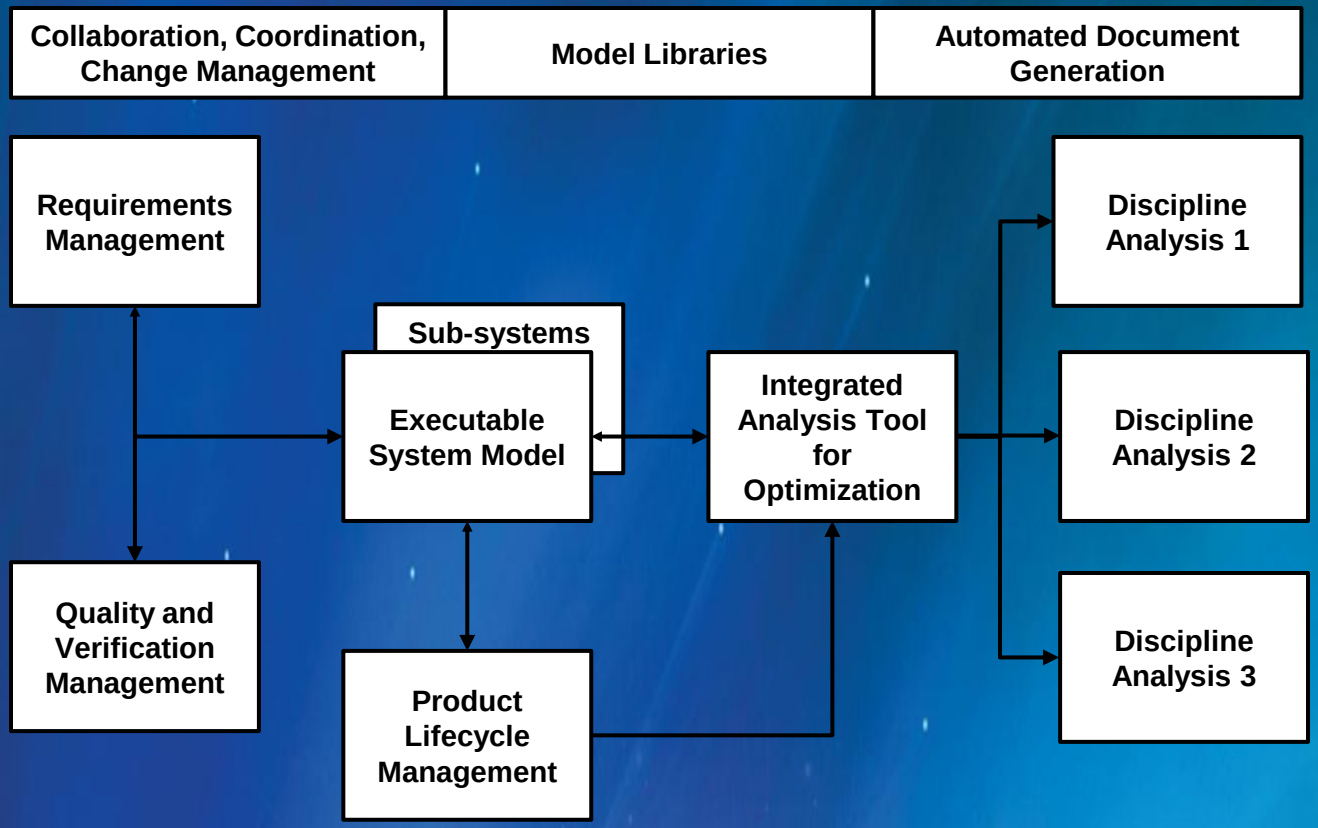
MBSE

- "…formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases"
- Game-changing approaches to system design are available, and advances are quickly being made in Model-Based Systems Engineering (MBSE).
- In contrast to the traditional document-centric approach to systems engineering.
- Models present an unambiguous, live representation of a system under development.
- Modern, model-based systems engineering methods are available which enable game-changing improvements to system design.
- Organizations are realizing better engineering and less overhead through these methods.

MBSE

- In the course of a traditional liquid rocket engine product development lifecycle, a multitude of documents and artifacts are produced.
- Meta-models provide for a “live” consistent set of model artifacts
- This meta-model is an evolving, cohesive representation of the system and serves as the live, single source of truth.
- Applications: System model; requirements management; quality and verification management; collaboration, coordination, change management; and automated document generation.
- As MBSE is propagated and applied more broadly in liquid rocket design and as more electronic elements are linked, game-changing efficiencies are possible.
- Couple these improvements with additive manufacturing capability, and there is a feasible path for the enormous improvements required for liquid rocket engine cost.

Instantiated MBSE Meta-Model



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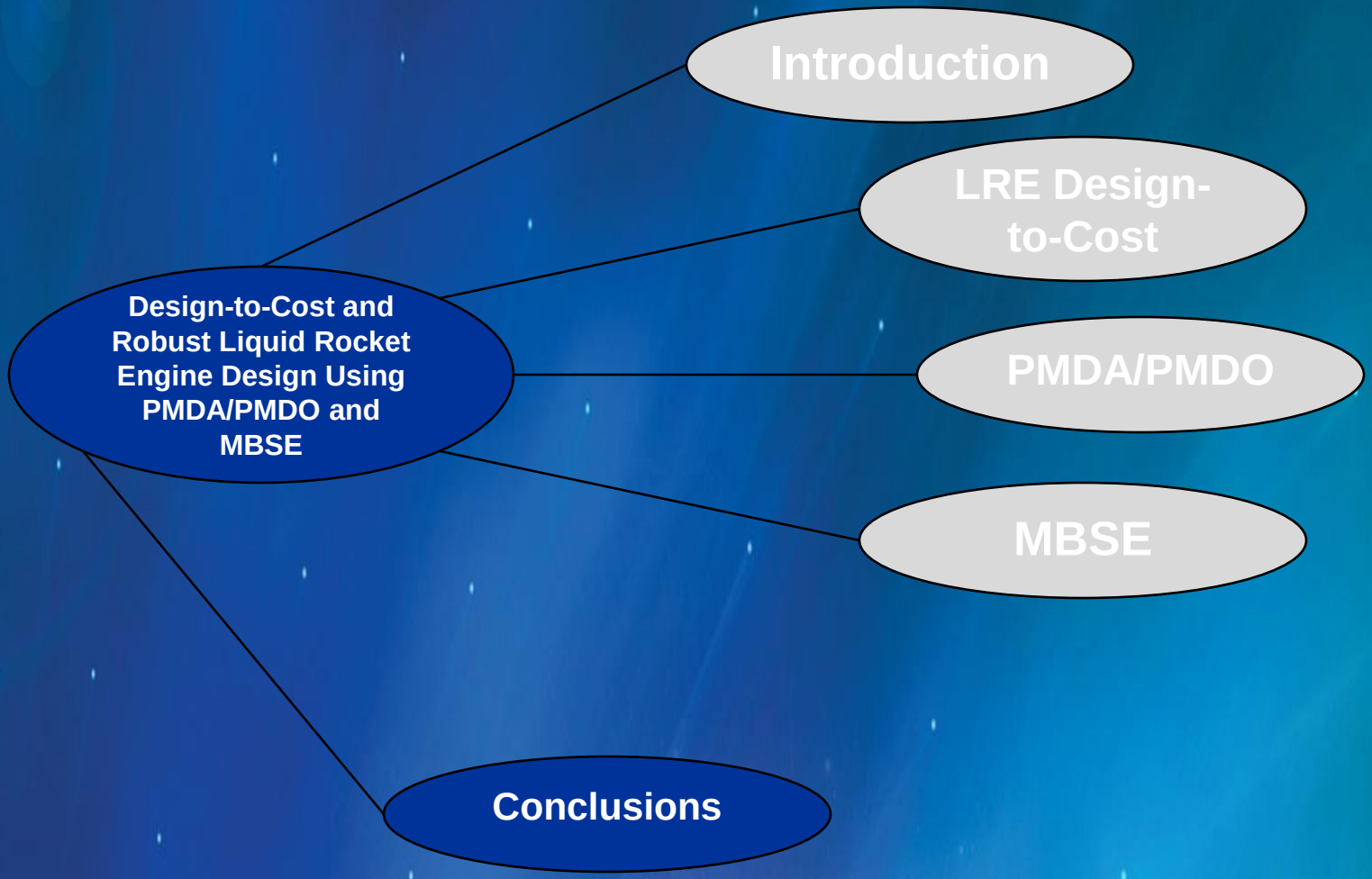
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- The alternate design philosophy of “design-to-cost” is experiencing a rebirth.
- Shifted emphasis on life cycle cost over maximum system performance; the new prominence is on understanding complex disciplinary interactions that drive the form, fit, function and cost of the final product.
- The two emerging analytical philosophies of PMDA/PMDO and MBSE can evolve the design-to-cost approach.
- PMDA/PMDO can optimize LRE configurations using operational constraints to achieve a robust design.
- MBSE formalizes the application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.
- The combination of these methods hold great promise in leading to better products, reducing costs and compressing development schedules.

Parting Thoughts on PMDA/PMDO and MBSE

AEROJET ROCKETDYNE

"There is just one thing I can promise you about the outer-space program: your tax dollar will go farther."

Wernher von Braun

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Q & A