# INTEGRATED SYSTEM TEST OF AN AIRBREATHING ROCKET (ISTAR)

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## Abstract

NASA is pursuing air-breathing propulsion in an effort to make future space transportation safer, more reliable and significantly less expensive than today's missions. Spacecraft powered by air-breathing rocket engines would be completely reusable, able to take off and land at airport runways and ready to fly again within days. A radical new engine project is called the Integrated System Test of an Air-breathing Rocket, or ISTAR. The flight-like engine system, called a rocket based combined cycle (RBCC), will be designed to accelerate a self-powered vehicle to more than seven times the speed of sound, demonstrating all modes of engine operation.

The development and ground test of a RBCC propulsion system is being conducted as part of the NASA Marshall Space Flight Center (MSFC) ISTAR program. Boeing - Rocketdyne, Aerojet and Pratt & Whitney have teamed as the Rocket Based Combined Cycle Consortium ($RBC^3$) to work the propulsion system development. Each company has complementary capabilities in the development of rocket, ramjet and scramjet propulsion systems for space launch vehicle systems. The teaming of these companies offers a unique opportunity to provide beneficial synergism by combining the best features of different approaches. The $RBC^3$ Team possesses the capability to perform the design, fabrication and test phases of the RBCC technology development, including flight demonstration

## Introduction

The NASA Advanced Space Transportation Program (ASTP) focuses technology development in four investment areas: (1) 2$^{nd}$ Generation Reusable Launch Vehicle (RLV), (which is part of the national Space Launch Initiative), (2) Spaceliner (3$^{rd}$ Generation RLV), (3) In-Space Transfer and (4) Space Transportation Research. The goal of all four elements is to put in place a technology base, which will dramatically improve reliability, safety, operability, and reduce the cost of space access. For the 3$^{rd}$ Generation RLV space transportation system (contemplated for 2025 IOC), the goals are two orders of magnitude increase in safety, and two orders of magnitude decrease in operating cost, while moving toward an airline type operation. The MSFC led program, under the guidance of ASTP, has shown a significant benefit from the use of airbreathing engine technology.

NASA is pursuing air-breathing propulsion in an effort to make future space transportation safer, more reliable and significantly less expensive than today's missions. Spacecraft powered RBCC propulsion would be completely reusable, able to take off and land at airport runways and ready to fly again within days.

## RBCC Reference Propulsion System

The RBCC engine for the 3rd Generation RLV vision vehicle would get its initial power boost from specially designed rockets integrated within a duct that captures air, an arrangement that improves performance about 15 percent above conventional rockets. Once the vehicle has accelerated to more than twice the speed of sound, the rockets are turned off and the engine relies solely on the oxygen in the atmosphere to burn its hydrogen fuel. When the vehicle has accelerated to more than 10 times the speed of sound, the engine converts to a conventional rocket-powered system to propel the craft into orbit.

A schematic of a notional RBCC reference propulsion system is shown in Figure 1. The various elements of the engine are identified. Several individual flowpaths, each separated by a strut, comprise the complete propulsion system and are integrated into a single engine system using common turbopumps, propellant feed lines, cooling systems and controls.

There are four primary modes of operation for this propulsion system. The air-augmented rocket (AAR) mode provides acceleration from air-launch through transonic, up to the point in the flight envelope where normal ramjet operation can be achieved. Transition to ramjet operation occurs about Mach 3 and fuel is injected at the rear of the struts in each flowpath. Acceleration continues until the Mach 6 – 7 range when the fuel has been transitioned to the forward section of the strut and scramjet operation has been achieved. In the reference system, around Mach 10, the engine transitions from pure scramjet operation to conventional rocket operation by closing the inlet cowl and re-lighting the rockets. The first three modes of operation are illustrated in Figure 2.

System benefits gained using an RBCC engine compared to pure rocket systems-include: 1) reduced takeoff weight, 2) aircraft-like operations, 3) reduced fuel utilization, 4) improved abort scenarios, 5) improved cross-range, 6) enlarged launch window, 7) increased system design margin.

## The ISTAR Program

Over the last four years, RBCC engine configurations have undergone more than 360 tests to help define requirements for an integrated engine system. The focus of the NASA / Marshall Space Flight Center (MSFC) Advanced Reusable Technologies (ART) project was to advance and develop RBCC engine technologies. The project was composed of several activities including RBCC engine ground testing, tool development, vehicle / mission studies, component testing / development, and flight demonstration studies. Two test engines have accumulated more than one hour of test time each, the most accrued on any single rocket-based, combined-cycle test article. Through this testing, engineers have demonstrated the performance of the engine in all its operating modes and transitions between various modes.

ASTP has created the RBCC engine technology project ISTAR – Integrated Systems Test of an Airbreathing Rocket – which offers high potential for addressing NASA's goals. The ISTAR RBCC Engine Project will enable a revolutionary step forward in Earth to Orbit propulsion. It is designed to make significant contributions to the needed technology base, both in hardware and performance concepts (macro-technologies) and in the needed underlying engineering technology base (micro-technologies). The project provides a technology test bed where RBCC engine technologies, and other technologies, can be demonstrated in both a ground and a test flight environment, and includes the design, fabrication, and test of an airframe-integrated, combined cycle engine system as a technology verification vehicle. In keeping with Enterprise and ASTP policy, the ISTAR Project strives to maintain close coordination with perspective beneficial users of its technology and strives to provide products that will be highly useful to these users.

NASA Marshall has brought together Government and Industry representatives to conduct a ground test of a Rocket Based Combined Cycle (RBCC) propulsion system. It is envisioned that a hydrocarbon fueled RBCC propulsion system, called the flight test engine (FTE), will be used to power a flight test vehicle from launch off a B-52 aircraft up to scramjet speeds of about Mach 7. The X43-B vehicle under consideration (Figure 3) for the flight test is a derivative of the current X-43 vehicle, which is commonly known as Hyper-X. The propulsion system development and ground test engine (GTE) will be conducted under the ISTAR program. NASA involvement in the ISTAR project includes project management and overall project technical lead at MSFC, inlet testing at Glenn Research Center (GRC) and Langley Research Center (LaRC), Vision Vehicle studies at LaRC, and flight demonstrator support from Dryden Flight Research Center (DFRC).

The conceptual design of the RBCC engine configuration is currently being developed under Phase I of the ISTAR program. Phase 1 of the ISTAR program, which began in November of 2001, will lead to a Systems Requirement Review in mid-2002. Detailed design of the ISTAR propulsion system will be initiated in Phase 2, leading to a ground test of a thermally and power balanced RBCC propulsion system in 2006. A parallel flight test demonstration of this propulsion system is anticipated to lead to a first flight in 2010.

## The RBC$^3$ Team Formation and Organization

To facilitate the development of the RBCC propulsion system and improve the focus of the ISTAR project, while working to preserve the U.S. high-speed space propulsion industrial base, the ISTAR RBCC Engine Project has encouraged teaming of the three major RBCC propulsion contractors who are potential providers of the technology. Industry representation includes Boeing's Rocketdyne Propulsion & Power, Gencorp's Aerojet and United Technologies' Pratt & Whitney companies. The Boeing Company provides vehicle support. The three propulsion companies have elected to combine their resources and to team for this program. The contractor team has been designated the Rocket Based Combined Cycle Consortium ($RBC^3$). Each company has complementary capabilities in the development of rocket, ramjet and scramjet propulsion systems for space launch vehicle systems. The teaming of these companies offers a unique opportunity to provide beneficial synergism by combining the best features of different approaches. The $RBC^3$ Team possesses the capability to perform the design, fabrication and test phases of the RBCC technology development, including flight demonstration.

Following concurrence by the Federal Trade Commission (FTC) of the consortium formation in August of 2000, the Rocket Based Combined Cycle Consortium ($RBC^3$) signed an official teaming agreement in March 2001. The teaming agreement, which represents a long term commitment (25 years) between the three companies, establishes company work / fee split, team organization, the exchange of proprietary information and a process for addressing changes in various aspects of Team activity under the Change Control Board (CCB).

A Joint Program Office (JPO), established within the teaming agreement, under the direction of the Program Director provides overall program management and coordination of the $RBC^3$ Team. The JPO consists of the Program Director, the Chief Engineer, the Systems Engineering Director, and the Business Manager. Rocketdyne is responsible for the management leadership of the Team, while Pratt and Whitney and Aerojet are responsible for the technical and systems engineering leadership, respectively, within the JPO.

An Executive Council (EC) was also established and chaired by one executive from each company. The EC provides direction and guidance to the JPO and reviews the adequacy of Team resources, the progress of the Team toward the RBCC Contract goals, allocation of resources, and the schedule of the RBCC Contract.

The organization structure for the $RBC^3$ team is based on the Integrated Product Development (IPD) approach. Integrated Product Development is a multi-discipline team approach, which can be used to solve even the most complicated and difficult engineering problems to produce a better product. Each of the team members have demonstrated that proper implementation of the IPD management process ensures efficient communication, team coordination and performance for the program, while evaluating and balancing all business issues and technical requirements during the life of the program. As a result, the IPD approach efficiently meets NASA's program objectives while reducing program costs. The IPD process consists of Systems Integrated Product Teams (SIPT's) and Integrated Product Teams (IPT's).

The SIPT's include Engine Systems and Flow Path teams. In the future, the Team will consider the benefit of adding a third SIPT for the Powerpack. SIPTs are responsible for system development in their respective areas of responsibility. The overall NASA Project structure and the $RBC^3$ Team organizational structure subset, including the Boeing vehicle involvement, is depicted in Figure 4.

Figure 5 shows the work breakdown structure for the ISTAR effort. Each element in the structure is a self contained, integrated product team (IPT). There are four major areas of the WBS: Program Management, Engine System, Powerpack (currently not active), and the Flowpath. For each major element, both the consortium and NASA have assigned a lead. The flowpath WBS elements contain the critical portion of effort for the ISTAR program. The consortium has subdivided the flowpath into major components in order to allow the key IPT's to be co-located. The major engine components have been subdivided as follows: the forward duct (all components forward of the rocket exit except the strut-rockets themselves), the strut rockets (including the integrated scram injectors) and the aft duct (includes the ram combustor and aft nozzle). In addition, a flowpath assembly integrated product team is tasked with coordination and integration of all three major components. Finally, there are two additional flowpath teams, one focused on the flowpath performance and the other on the integrated flowpath testing efforts.

## RBCCC Team Approach

### Performance Requirements Review

The ISTAR project goal is to develop a flight-weight rocket based combined cycle engine system ground test bed capable of accelerating a self-powered vehicle from Mach 0.7 to Mach 7. Although ISTAR is an engine development program, all of its requirements must be derived from the integrated vision vehicle / engine system.

The ISTAR performance requirements review (PRR) was held by NASA in April 2001 with the $RBC^3$ Team and the vehicle development support. The main objectives of the PRR include the assessment of project requirements and the ability to meet them with an acceptable level of risk. A final product of the PRR was the Systems Requirements Document (SRD) for the ISTAR RBCC Engine / X-43B Flight Demonstrator Project. The SRD provided the top-level integrated vehicle / engine system requirements.

### Risk and Opportunity Approach

The RBC3 Team has used a risk and opportunity (R & O) approach to provide NASA with a probability assessment of success, based upon proposed cost and scope. The R & O tool has been used at all levels of the project to provide ROM cost estimates for identified risks and opportunities. A probability of occurrence was also developed for each risk and opportunity. Each risk or opportunity could affect program cost, schedule or both.

The R & O process, shown in Figure 6, was performed at each WBS level. A Monte Carlo analysis provided management a tool to determine where the “heavy hitters” were located, where reallocation of resources could be needed and where scope adjustment may be warranted to meet the programmatic probable success criteria. NASA participated in this R & O analysis by providing input in the risk and opportunity assessments and also concurring with the selected level of probability of success (or level of risk) for the ISTAR program. The results of the R & O Monte Carlo analysis showing probability of success versus program cost are shown in Figure 7 for Phase I of the ISTAR program.

Systems Engineering Organization

The RBC$^3$ Systems Engineering organization is comprised of team leads from each of the consortium members. The organization also includes active participation from NASA and its consultants. Systems Engineering has lead responsibility for the collection of system design and verification requirements, configuration control documents, risk management plans, quality assurance plans, and engineering specialty plans (safety, reliability, maintainability and integrated logistics support). Within each of these areas, Systems Engineering leads the management of requirements/plans with inputs from the customer, Chief Engineer, Program Managers, and SIPTs, maintains the controlling documents, and leads the internal review efforts to verify compliance with the plans. Those documents include the Interface Control Documents (ICD's), Systems Requirements Documents (SRD's) and Component Requirements Documents (CRD's). Systems Engineering also prepares and maintains the Systems Engineering Management Plan (SEMP).

Common Team Tools

A common set of team tools was determined as part of the Jumpstart Phase of the ISTAR program. The set of tools identified all of the common tools used by members of RBC$^3$ and NASA. The tools included analysis programs, design program (CAD) and the general computer office suite.

The RBC$^3$ Team is using a secure server site, allowing access to all RBC$^3$ Team members, including NASA team members. It provides the repository for all ISTAR information. NASA also has an official server site for submittal of Data Requirements Documents (DRD's). This official NASA program site is called the Space Transportation Information Network (STIN). All official NASA ISTAR documentation is placed on this site, which is also accessible by team members.

Continuous Risk Management

Continuous risk management (CRM) is a key element in the ISTAR program. CRM includes the standard risk management elements of identify, analyze, plan, track, control, communicate and document. CRM also emphasizes the need for continuous assessment and update of the process, as the program matures and events shape or change the course of the development. Part of overall risk management involves the evaluation of the following key program data: schedule, critical path analysis, hazard analysis, key project metrics, reliability analysis, cost analysis, historical data, etc.

Value Streaming

The ISTAR program will use Value Streaming to determine where the program should best spend its technology funds to reduce technical risk. Design concepts and approaches are first documented in sufficient detail to be able to assess the risk associated with each along with any shortfalls that exist in basic engineering capabilities. Examples of the level of detail that would be used in this initial step are: 1) design requirements and their sources, including flow-down and derived requirements and/or key assumptions, 2) summary review of hardware design concepts, including inboard and outboard profiles showing expected temperatures and loads along the flow path that are driving the design of the system/subsystem, and 3) identification of any critical program-unique technical concerns and consequences. Once the information is gathered, recommendations are made as to where best to spend technology money to reduce risk, such as, alternate design solutions or improvements in the materials, engineering tools and/or data bases to validate the design. The outcome of the Value Streaming process is the identification of specific risks and the mitigation plans for each, which are provided to the ISTAR team for input into the Risk Management database.

Utility Analysis and Trade Factors

Another key tool employed by the consortium is determination of the trade factors that the design teams will use in their decision-making. This is done via the Utility Analysis process that identifies the key attributes of the ultimate design solution, determines the ranges over which those attributes can vary, and quantifies the "utility" of the solution over these ranges. Then specific trade factors can be determined by the derivatives of the slopes for the point that the design is currently at. These curves and trade factors can then used to make design or programmatic decisions.

Non Advocate Reviews

The $RBC^3$ Team provides support to NASA for annual Non Advocate Reviews (NAR) presented to top NASA center management. The review provides an assessment of the state of the project definition in terms of clarity of objectives and thoroughness of technical and management plans, technical documentation, alternatives explored, and trade studies performed. The NAR also seeks to assess the cost and schedule estimates, and the contingency reserves in these estimates. A NAR is generally held once a year.

Purple Team Reviews

Major proposal submittals by the $RBC^3$ Team to NASA are reviewed through a "purple team" process that has IPT leads summarizing tasks, schedules, costs, risks / opportunities, and major assumptions / issues. This summary is documented in purple team charts, which are presented by the IPT leads to the $RBC^3$ JPO, Program Managers, SIPT's and NASA representatives. The purple team review provides a joint NASA / $RBC^3$ overview of proposed tasks and provides a forum to develop priorities and to make team adjustments to tasks, schedules and cost levels.

Joint NASA / $RBC^3$ Program Planning

NASA and $RBC^3$ maintain a master program schedule that details the program plan through the Ground Test Engine (GTE) program. This master schedule is a joint endeavor that requires planning and input from all $RBC^3$ members and the NASA centers involved in ISTAR. This program planning has been invaluable in developing look ahead and "what-if" scenarios as year-to-year budget priorities and program goals are updated with time. The master schedule provides a tool to measure impacts on overall program milestones and budgets against any potential program adjustments.

## ISTAR Program Details

### Jumpstart Phase

The first phase of the ISTAR program, called "Jumpstart", selected the initial team engine concept. A flowpath selection committee determined the engine down select. This initial flowpath selection has been fully documented in Reference 1. The Jumpstart Phase ended at the Conceptual Design Review (CoDR) held in June of 2001. The net results of the CoDR were that the engine selected did not meet the Mach 7 mission requirements. Shortfalls in component performance and a substantial weight growth determined, during the Jumpstart Phase, led to a maximum Mach number of 4.3.

### Transition Phase

During the next phase of ISTAR, the Transition Phase, a "Tiger Team" was formed to focus solely on improving the capabilities of the engine selected in Jumpstart. The Tiger Team made significant progress and, in the span of just over one month, the team decreased the engine weight by 2200 lbs and increased the maximum Mach number to M=6.8. However, after significant consideration, NASA asked the consortium to investigate alternate configurations.

For this selection, a selection committee was formed, consisting of NASA, the Boeing vehicle partners and the consortium. The committee collectively selected new flowpath lines, with the caveat that the new lines had to have experimental substantiation. Three primary candidates were selected for further study.

The three engine concept candidates included a fixed geometry architecture (Configuration X), a limited variable geometry approach (Configuration Y) and a more complex variable geometry system (Configuration Z). For this evaluation, the consortium established the design, performance and weights of all three concepts. In addition, uncertainty bands were calculated for the performance and weight estimates. Inter-company teams were created to evaluate the design, weight and performance of the concepts. The performance team evaluated the component efficiencies and uncertainties for each candidate architecture. Potential weight growth was included in the final analysis.

Once the performance, the weight and the uncertainty bands were established for each concept, the engine was "flown" via an electronic spreadsheet. The spreadsheet estimated the vehicle / engine performance across the trajectory range. Inputs for installed engine / vehicle drag were obtained from the Boeing Company. The fly-off spreadsheet produced an estimate for the residual fuel at Mach 7 and the maximum Mach number the engine/vehicle combination obtained. The results from the fly-off spreadsheet are shown in Figure 8.

All engine concepts achieved the Mach 7 requirement. The "Y" engine was selected because it had the least mission performance uncertainty, the highest fuel margin at Mach 7 and the flexibility of variable geometry for increased margin.

Phase I

During the current phase of the program, called Phase I, the activities are focused on the Flight Test Engine (FTE). During Phase II, the focus will switch to the Ground Test Engine (GTE). The principal goals of the Phase I effort are to increase the design maturity of the engine and to complete the System Requirements Review (SRR). Additionally, test efforts will be started for the critical performance elements.

Prior to Phase I, NASA made the decision to switch the oxidizer from liquid oxygen to 90% hydrogen peroxide. This decision was driven predominantly by the safety concerns for the B52 with the use of liquid oxygen. A trade study determined that the greater density of hydrogen peroxide offset its lower performance, such that the net effect of switching oxidizers was a negligible change in maximum vehicle Mach number.

The Phase I design effort is divided into two design cycles. During each cycle the design fidelity will be increased and the engine performance developed such that Boeing can evaluate the engine / vehicle combination. The flowpath and the entire engine system will be integrated on the vehicle. The mass properties and volumes of all the components will be reevaluated. The net result of these design cycles will be an increase in fidelity of the engine design and the maximum vehicle Mach number.

Several trade studies are currently being worked as part of the early Phase I effort. These trade studies include optimization of the rocket strut location, the rocket shape, the film cooling evaluation, the location of the scram injectors, the number of catalyst beds and modular assembly versus panel assembly.

Near the mid year point of CY 2002, the Systems Requirements Review (SRR) will be held. This review will define the top-level flight engine system requirements such as engine weight, performance (Isp, thrust, $\eta_c$, etc.), engine envelope, structural attachments, flow rates, pressures, temperatures, etc. For the final gate of the SRR, the engine must close with vehicle such that the Mach 7 goal is met with an acceptable level of confidence.

Combustion of liquid kerosene (JP-7) at the ramjet takeover point has been considered one of the critical data items required for mission success. A test effort will be started in Phase I, addressing this concern. Additionally, early development work on the rockets is required in order to meet the GTE test date. A full-scale injector with a workhorse chamber will be tested early in Phase II. Test planning, design and fabrication of the hardware will be conducted in Phase I. Other tests under consideration include a fuels characterization task to establish the cooling capabilities and properties of JP-7 and a sub-scale integrated engine test focused on the air-augmented rocket performance.

## Conclusion

The development of a ground test engine for a Rocket Based Combined Cycle (RBCC) propulsion system is being conducted as part of the NASA Marshall Space Flight Center (MSFC) ISTAR program. Boeing - Rocketdyne, Aerojet and Pratt & Whitney have teamed as the Rocket Based Combined Cycle Consortium ($RBC^3$) to work the propulsion system development. Each company has complementary capabilities in the development of rocket, ramjet and scramjet propulsion systems for space launch vehicle systems. Synergism between the three companies and NASA has already produced some unique tools such as: risk & opportunity analysis, continuous risk management, utility analysis, value streaming and purple team reviews.

The team is currently conducting Phase 1 of the ISTAR program with the primary goals of increasing the design maturity of the flight test engine and conducting the Systems Requirements Review. During Phase 2 of the program the design, fabrication and test of a full-scale ground test engine will be completed.

The $RBC^3$ Team possesses the capability to perform the design, fabrication and test phases of the RBCC technology development, including the eventual, flight demonstration.

## Acknowledgement

The authors thank Mr. J. Craig McArthur, ISTAR Project Manager, George C. Marshall Space Flight Center, NASA for his dedication, leadership and direction in managing, through the Joint Program Office, the three ISTAR Consortium propulsion companies.

## References

1. Faulkner, Robert, "Integrated System Test Of An Airbreathing Rocket (ISTAR)," AIAA 2001-1812, June 2001.

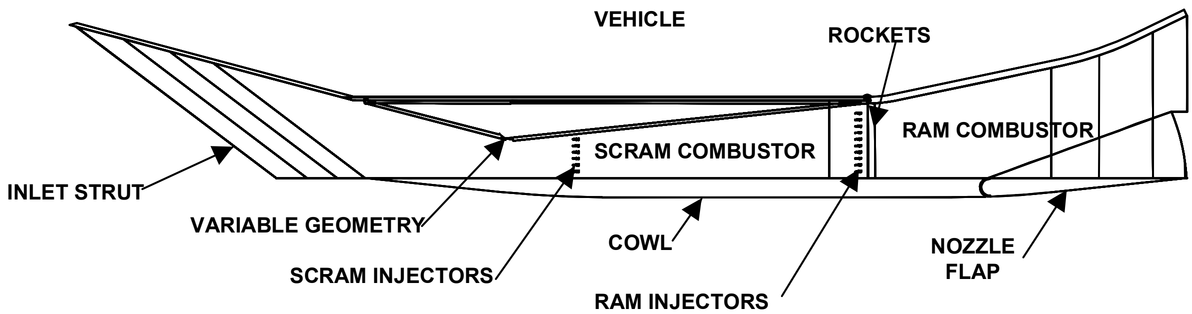


Figure 1: RBCC Reference Propulsion System Schematic

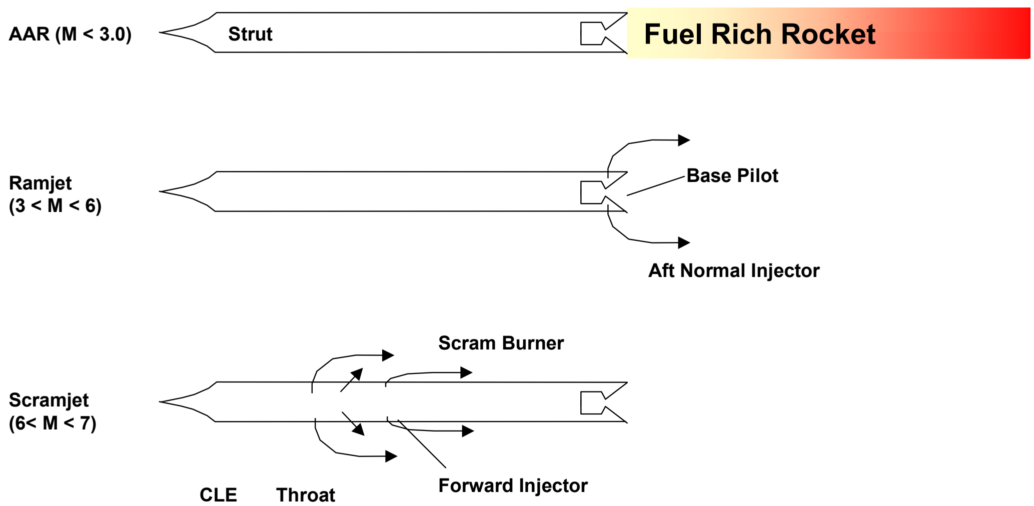


Figure 2: RBCC Modes of Operation

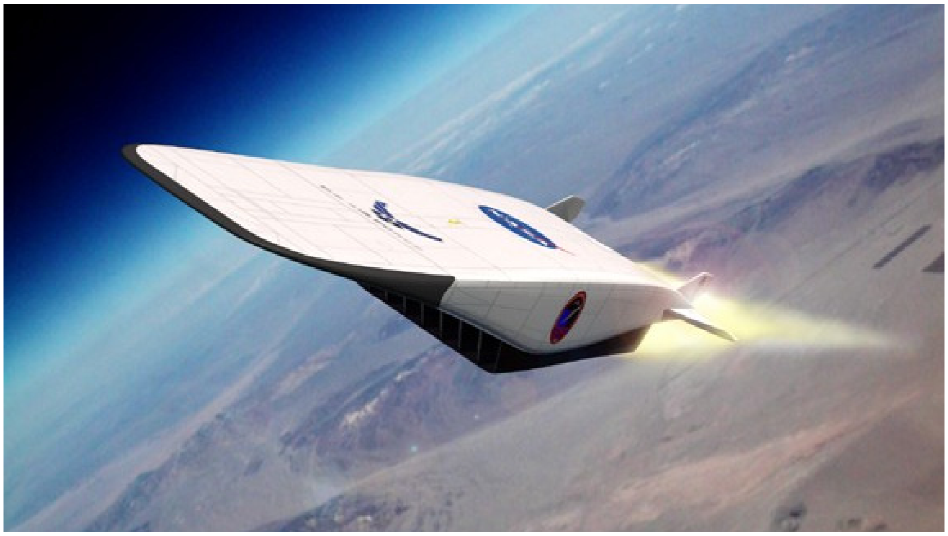

Figure 3: Notional X43-B Flight Demonstrator

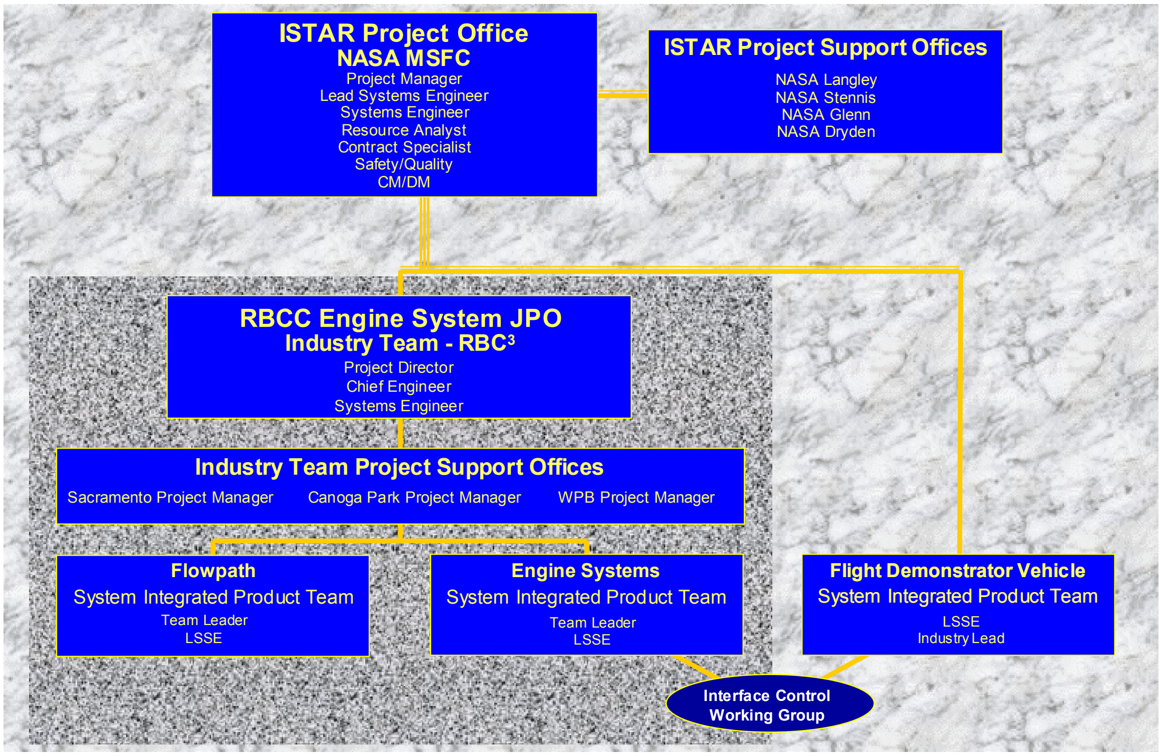


Figure 4: ISTAR / RBC3 Project Structure

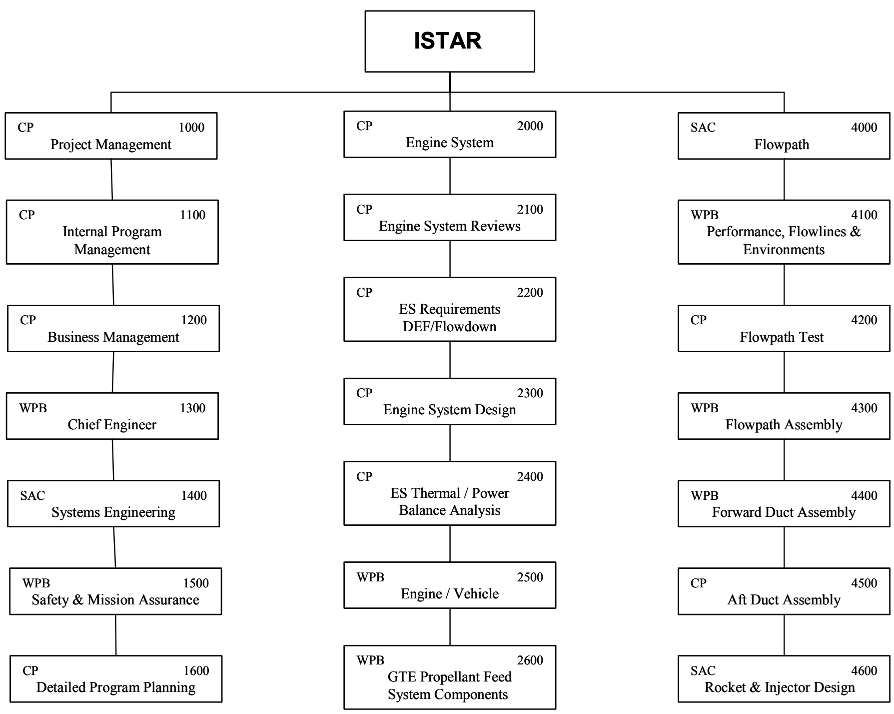


Figure 5: ISTAR Work Breakdown Structure

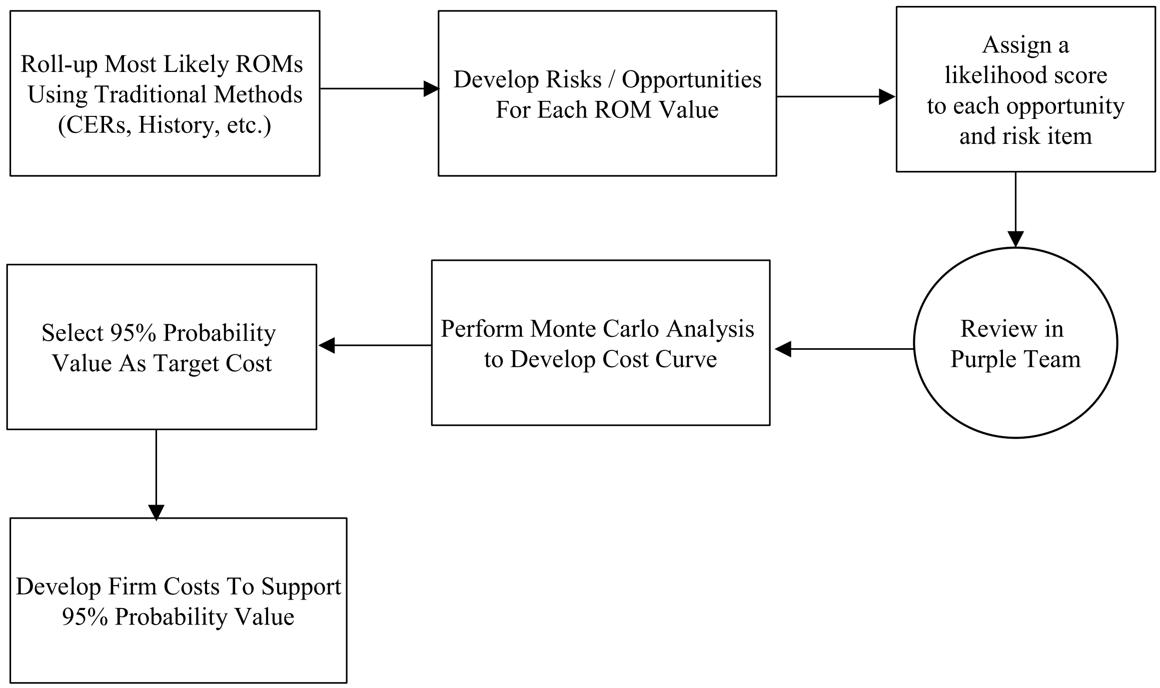


Figure 6: Three Point Cost Estimating Process

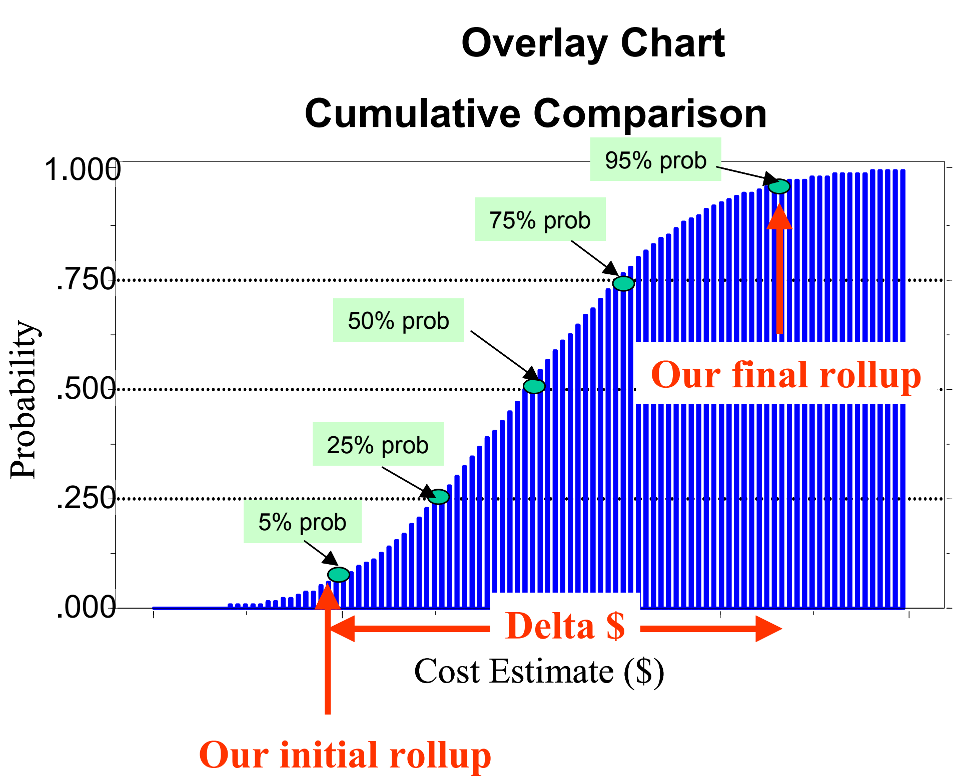


Figure 7: Monte Carlo Results - Cost / Schedule Assessment Performed

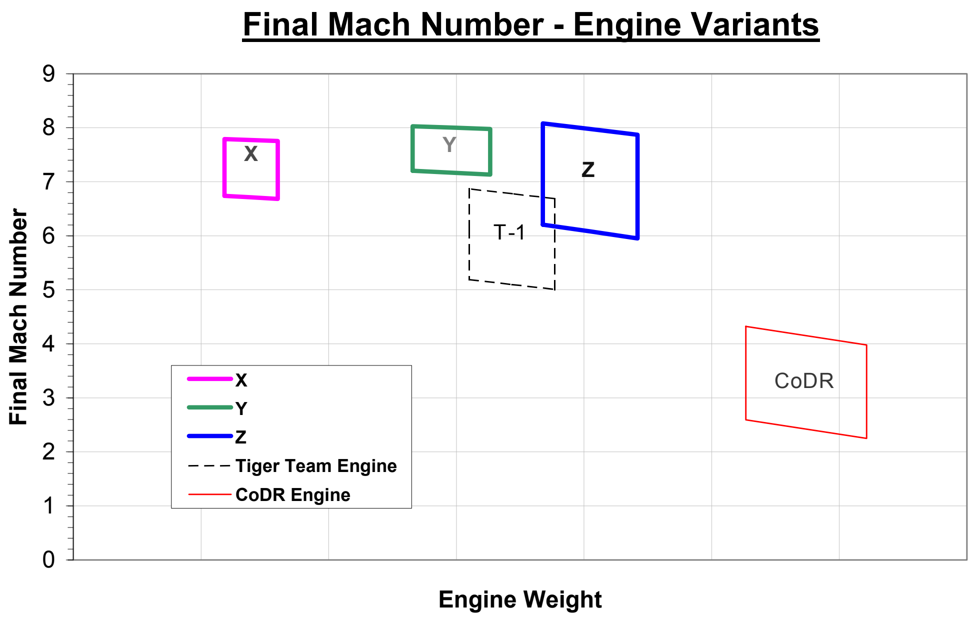


Figure 8: Engine Selection Results