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Information Flow in the Launch Vehicle Design/Analysis Process

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December 1999

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FOREWORD

In 1997, at the request of the Advanced Space Transportation Office, Marshall Space Flight Center (MSFC) initiated planning to perform an in-house design for the low-cost expendable launch vehicle referred to as Bantam. Dr. Randy Humphries, Director of the Structures and Dynamics (ED) Laboratory, formed a team to define a Bantam vehicle design process with emphasis on the design/analysis functions performed by the ED Laboratory. This team developed a collection of information documented in reference1 that defined a design/analysis process for the Bantam vehicle. The N×N diagram format was used to display the interdisciplinary interactions among the design/analysis functions. This information proved useful to the in-house development of a reference architecture for the Bantam. The reference architecture and design process report were made available to the contractors bidding to develop competing conceptual designs in response to NASA Research Announcement, NRA–2.

After completion of the Bantam vehicle design process study, Dr. Humphries tasked a new ED team to define a design process that is generically applicable to classes of launch vehicles currently envisioned in NASA's advanced space transportation initiative. Additionally, the task was limited to focusing on the interactions of design/analysis functions performed by the ED Laboratory during phase C.

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LIST OF ACRONYMS

ABL	ablation
ACE	aerochemical equilibrium
ALS	Advanced Launch System
C&DH	communications and data handling
C&DM	control and data management
CAD	computer aided design
CCB	configuration control board
CG	center of gravity
CID	cable interconnect diagram
CIL	critical items list
CMA	charring material ablator
COTS	commercial off the shelf
DDT&E	design, development, test, and engineering evaluation
DeMAID	design manager's aid for intelligent decomposition
ED	Structure and Dynamics Laboratory
EEE	electrical, electronic, and electromechanical
EGSE	electrical ground support equipment
ELV	expendable launch vehicle
EMI	electromagnetic interference
EMS	engineering modeling system
EPA	Environmental Protection Agency
EPS	electrical power system
FEAS-M	failure environment analysis system-MSFL
FEAT	failure environment analysis tool
FEM	finite element model
FIRM	full iterative relation matrix
FMEA	failure modes and effects analysis
FMR	flight mission reserve
FPR	flight performance review
FTC	fault tree compiler
GPS	global positioning system
GLOW	gross lift-off weight
GSE	ground support equipment
HA	hazard analysis
I/F	interface
IP&CL	instrumentation program and component list
I_{sp}	specific impulse
ISSI	International Space Systems Incorporated
KSC	Kennedy Space Center

LIST OF ACRONYMS (Continued)

lox	liquid oxygen
LMR	launch mission reserve
MARSYAS	Marshall systems for aerospace simulation
MIUL	material identification and usage list
MOI	moment of inertia
MPS	main propulsion system
MSFC	Marshall Space Flight Center
MST	mission support team
MUA	material usage agreement
NDE	nondestructive evaluation
NLS	National Launch System
NPSP	net positive suction pressure
OBC	onboard computer
OPS	operations
OSHA	Occupational Safety and Health Administration
PATRAN	a finite element preprocessor and postprocessor
POGO	pogo suppression system
POST	program to optimize simulated trajectories
PRACA	problem reporting and corrective action
PU	propulsion unit
QRAS	quantitative risk analysis system
RBCC	rocket-based combined cycle
RCS	reaction control system
RF	radio frequency
RLV	reusable launch vehicle
SINDA	systems improved numerical differencing analyzer
S/W	software
TCS	thermal control system
TPS	thermal protection system
TRASYS	thermal radiation analysis system
TRL	technology requirements level
TVC	thrust vector control
VAB	vehicle assembly building
WBS	work breakdown structure

TECHNICAL MEMORANDUM

INFORMATION FLOW IN THE LAUNCH VEHICLE DESIGN/ANALYSIS PROCESS

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1. INTRODUCTION

For today's competitive environment, it is imperative to reduce the time and cost of launch vehicle design projects. Launch vehicle design involves the work of many disciplines; each dependent on the work of other disciplines. To achieve faster, better, and cheaper designs organizations are flattening and new projects are beginning with teams distributed across both industry and government agencies. In this environment it is important that design engineers see the larger picture so they understand the connections between what they do and where it fits in the overall design process of the project. It is also important that design managers understand the information flow between disciplines and can track and control it during the design process to assure that the right people receive the right information at the right time.

Another document, "Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned" is a comprehensive treatment of the entire design process. It describes the overall process and issues such as other design phases, merging of the discipline and subsystem aspects of the design process, and iterative nature of the process.

1.1 Purpose

This report describes the information flow and interactions between the design functions involved in phase C of the launch vehicle design process. It is intended to provide engineers with an understanding of the connections between what they do and where it fits in the overall design process of the project. It also provides design managers with a better understanding of information flow in the launch vehicle design cycle.

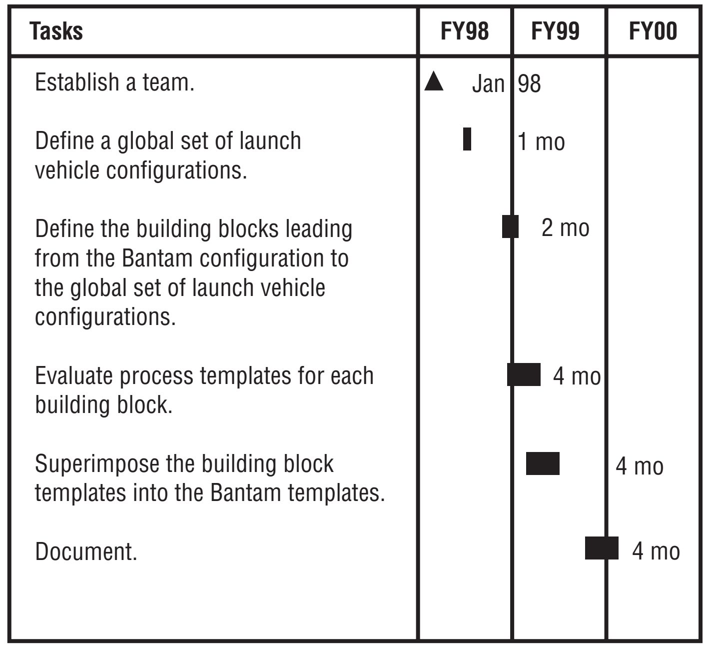
1.2 Scope

Figure 1 summarizes the goals and objectives, schedule, and achievements to be realized at completion of this study (as originally planned). The task objective is to describe the information flows and interactions between the design functions involved in the launch vehicle design process with focus on the design functions residing in the Structures and Dynamics (ED) Laboratory. The design functions residing in the ED Laboratory are Vehicle Configuration and Design, Performance and Trajectories, Aerodynamics and Induced Environments, Structural Analysis, Thermal Analysis, and Guidance and Control. The process description must be generic and applicable to the diverse launch vehicle concepts being considered for NASA's advanced space transportation requirements—everything from conventional expendable launch vehicles (ELV's) with solid rocket propulsion to reusable launch vehicles (RLV's) with air-breathing propulsion systems.

Goals and Objectives:

- Using the design process templates developed for the Bantam launch vehicle as a point of departure develop templates which describe ED Laboratory's design process for various types of launch vehicles.
- Use a building block approach which shows the relationship between the design process and the launch vehicle configuration.

Schedule:



Achievements:

- Knowledge capture for future launch vehicle design solutions
  - – Transfer of knowledge to less experienced personnel
  - – Knowledge base useful for developing task statements and identifying skill and resource requirements.
- Enable process optimization.

Model:

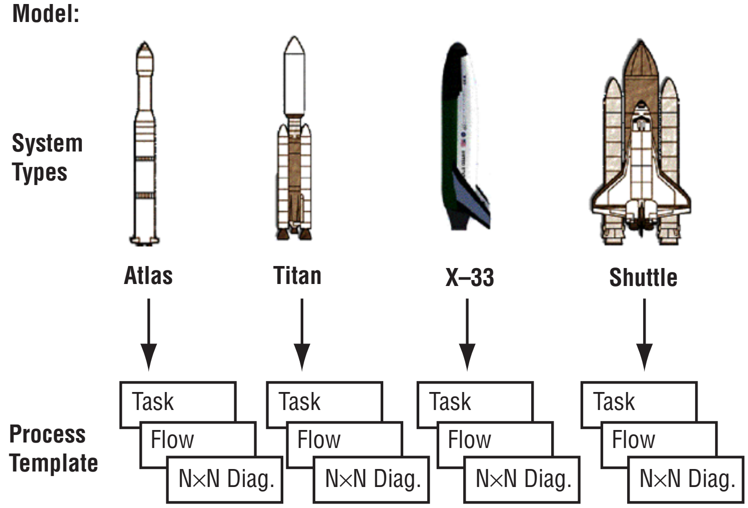


Figure 1. MSFC's launch vehicle design and analysis.

2. APPROACH

The design process described in reference 1 for the Bantam vehicle (an ELV) was the point of departure for this study.

An ad hoc team was formed. The team was comprised of a senior representative from each of the ED Laboratory's design functions and augmented with contractor members bringing additional expertise and experience in the areas of launch vehicle design, air-breathing and rocket-based combine cycle (RBCC) propulsion systems, and systems engineering.

As a first step, the team examined the launch vehicle concepts being considered for NASA's advanced space transportation requirements. The vehicle configuration tree, figure 2, encompasses the concepts.

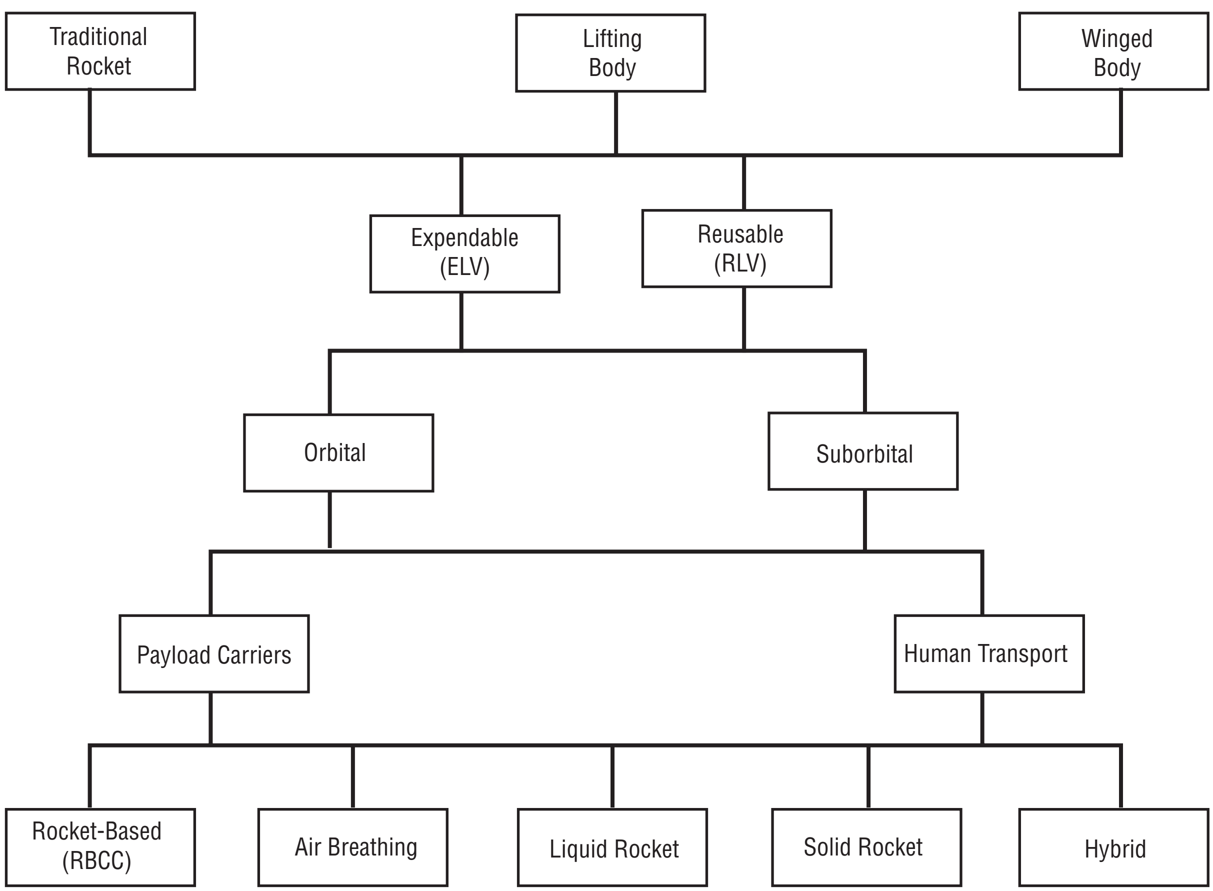


Figure 2. Vehicle configuration tree.

Second, each ED design function reviewed the vehicle configuration tree and identified those configuration characteristics that affect its design process. The configuration characteristics that were determined to be process discriminators were the ELV, RLV, and RBCC.

Finally, each ED design function revised the Bantam process templates to include the data flows and discipline interactions required for the phase C design of the ELV, RLV, and RBCC vehicle configurations.

2.1 Process Templates

Three types of templates are used to model the flow of information at a first level:

- An N×N diagram is used to show the inputs and outputs of the design disciplines
- Discipline flow diagrams
- Discipline task descriptions.

2.1.1 N×N Diagram

The N×N diagram, a functional analysis tool described in appendix A, displays the interdisciplinary interactions and interfaces among the design and analysis functions performing the detailed design phase (i.e., phase C design). To improve the readability of the diagram, it is presented as a two-part table (table 1): the first part shows the top half of the diagram, and the second part shows the bottom. The ED design functions are placed on the diagonal in the upper left partition; the remaining system design functions are placed on the diagonal in an arbitrary sequence. Unique terms used in the N×N diagram are defined in appendix B.

The basic N×N diagram is augmented here by the addition of two rows at the top, labeled External Inputs and Natural Environment Inputs. The External Input row identifies the project requirements, goals, and guidelines levied on the vehicle design functions and also includes the design databases transmitted by the Preliminary Design Review. The design functions' outputs are listed in the rows and the design functions' inputs are listed in the columns. A blank row-column intersection indicates no interface between the corresponding design functions. In addition to generating data as required inputs for other design functions, each design function also produces data required to evaluate, verify, and validate the design. These products are listed in the column on the right labeled Products. The row labeled Natural Environment Inputs identifies natural environment data items required by the design functions.

Items below the diagonal show information being fed back into the process and, hence, indicate iterations. An optimized N×N diagram is one that has been modified to resequence the diagonal functions into an arrangement that minimizes the number of iterations required to perform the design cycle and, therefore, reduces cycle time. Optimization of the N×N is required to develop a schedule of the design function tasks that achieves the shortest cycle time. The N×N diagram shown here has not been optimized. This N×N diagram is intended to provide engineers with an understanding of the connections between what they do and where it fits in the overall design process. It also provides design managers with a better understanding of information flow in the launch vehicle design cycle.

Table 1a. N×N diagram, top partition.

Outputs (columns) / Inputs (rows)

	A	B	C	D	E	F
External Inputs	• Project groundrules • Design-to-cost goals • Production operations • Ground operations • Critical interfaces • Subsystem definition • EPA and OSHA constraints • Environmental operations constraints • Preliminary design concept and database	• Mission definition • Initial performance • Vehicle coordinate system • Launch pad geometry • Project groundrules • Redundancy requirements • Preliminary design concept and database • Range safety constraints	• Project groundrules • Design-to-cost constraints • Launch pad geometry • Preliminary design outer moldline • Conceptual moldline	• Project groundrules • Design-to-cost constraints • Factors of safety criteria and fracture control requirements • Launch platform finite element model	• Project groundrules • Design-to-cost goals • Preliminary design concept and database	• Project groundrules • Design-to-cost goals • Launch probability requirements • Preliminary design concept and database
Natural Environment Inputs	• Ground wind profiles • Launch pad environments • Use and operational environments	• Atmospheric model • Ascent wind models • Project groundrules • Launch pad environments	• Ground and ascent wind profiles • Atmospheric models • Launch stand ambient temperatures	• Ground and ascent wind models	• Launch pad environments	• Atmospheric model • Wind models (ground and ascent) • Gust models • Launch pad environments
1	3.1 Vehicle Configuration and Structural Design	• Engine alignment tolerances ••• Vehicle geometry drawing	• Vehicle moldline • Vehicle geometry • Protuberance geometry • Engine placement geometry	• Vehicle geometry • Vehicle and pad interface geometry • Holddown and release mechanism • Structural details • Component installations • Shock sources	• Vehicle and elements - configuration definition - material - dimensions	• Overall vehicle dimension • Engine alignment tolerance • Feedline drawings
2	• Staging requirements • Propellant requirements • Number of engines • Performance updates •• Entry propellant weight	3.2 Performance and Trajectories	• Ascent trajectory sets (altitude, velocity, time histories) and engine operating conditions • Entry trajectories ••• Airflow history to inlet • Constraints ••• Mach transitions	• Loads trajectory data	••• Ascent, cruise, loading requirements	• Time history • Max Q • Reference trajectories ••• Angle of attack, airflow ••• Ascent, cruise, landing requirements
3	• Pressure vent sizes and locations • Moldline update including airframe and engine design	• Vehicle ascent aerodynamics • Heating indicators •• Vehicle and stage entry aerodynamics ••• Engine inlet flowfield definition • Engine installed thrust throughout trajectory	3.3 Aerodynamics and Induced Environments	• External aerodynamic pressure distributions • Compartment pressures • Protuberance airloads • Acoustic and overpressure definition • Fluid dynamic loads (buffeting)	• Ascent aero heating histories • Entry aero heating histories • Compartment flow rates • Plume heating environments	• Vehicle aerodynamics • Guidance and control instrumentation locations
4	• Structural sizing • Loads and deflections • Margins of safety • Propellant slosh baffle sizing	• Q_α, Q_β constraints and structural load	• Structural deflections	3.4 Structural Analysis	• Temperature gradient design limits	• Vehicle flex-body modes • Propellant slosh modes • Propellant feedline flex modes • Q_α, Q_β and structural load constraints
5	• Thermal protection system sizing • Cryogenic insulation sizing • Active thermal control system sizing • Temperature sensor locations	•• Wall and surface temperatures • Heating rate or temperature indicators	• Heating constraints •• Wall and surface temperatures	• Structural temperatures and gradients	3.5 Thermal	
6	• Maximum engine deflection • Control sensor locations • Control surface deflection requirements	• Autopilot definition • Guidance system inputs ••• Modified autopilot to reflect a control law for airflow to inlet • Control surface mixing logic		• Slosh damping requirements • Q_α versus Q_β envelopes • Flex body mode frequency constraints • Autopilot definition • Vehicle transient response to wind disturbances		3.6 Guidance and Control
7	• Mass properties control plan • Documented control weights • Centers of gravity • Moments of inertia	• Documented control weights • Weights • Centers of gravity • Moments of inertia	• Documented control weights • Centers of gravity	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia • Mass versus time
8	• Propellant inventory • Propulsion system layout • Tank pressures • Propellant level sensor locations ••• Forebody (iterate required air volume) ••• Staging requirements ••• Propellant requirements ••• Number of engines ••• Performance updates •• Entry propellant weight	• Propellant load • Engine performance (I_{sp}, thrust) ••• Expected engine mach transitions ••• Inlet captive volume ••• Recovery pressures ••• Forebody (required air volume) ••• Body, for airflow as a function of mach number ••• Mach transitions	• Engine dimensional and operational characteristics • Turbine exhaust definition • On-pad effluent definition ••• RBCC exhaust conditions ••• Forebody inlet performance requirements ••• Transition mach number	• Ignition and shutdown thrust transients • Ignition and shutdown timing sequence • Steady state thrust oscillation • Ullage pressure and tank fill heights versus flight time ••• RBCC exhaust and thrust ••• Forebody inlet	• Ground hold conditions • Heat load requirements for propellant conditioning • Chill down requirements • Engine configuration • Engine operating characteristics • Engine thermal requirements	• Thrust vector control gimbal capability (degree and rates) • Feedline layout • Kinematic analysis • PU system definition ••• a airflow for ascent, cruise, and landing ••• Air capture transition

	G	H	I	J	K	L
External Inputs	• Project groundrules • Design-to-cost goals • WBS • Vehicle coordinate system • CCB directives	• Project groundrules • Design-to-cost goals • Technology requirements (TRL Level) • Engine interface • Redundancy requirements • Programmatic constraints	• Project groundrules • Design-to-cost goals • EPA and OSHA constraints	• Instrumentation program and component list redundancy requirements • Verification requirements • Operational timeline • EEE parts requirements • EPA and OSHA constraints	• Redundancy requirements • Verification requirements • Operational timeline • Operational life • External interfaces • EEE parts requirements • EPA and OSHA constraints	• Project groundrules • Design-to-cost goals • Facility capabilities
Natural Environment Inputs		• Launch pad environments	• Use and operational environments		• Lightning • Atmospheric constituents • Clouds - fog • Precipitation • Corona prevention	• Atmospheric constituents • Lightning • Humidity • Precipitation • Severe weather • Ground winds
1	• Component weight estimates • Vehicle geometry • Parts list • Cross-sectional properties	• Vehicle configuration and tank geometry • Vehicle dimensions • Line routing zones • Pressurant bottle locations ••• Preliminary air column ••• Profile	• Construction type (honeycomb, isogrid, etc) • Critical dimensions • Tolerances • Drawings	• Vehicle dimensions • Vehicle configuration	• Power return through structure • Component installation	• Hardware design • Verification requirements • Transportation requirements
2	• Propellant load versus time • Burn times • Jettison times • Residuals at main engine cutoff, etc.	• Vehicle mass versus time • Thrust, acceleration and pressure versus time • I_{sp} (flow rates) • Usable propellant requirements • Axial acceleration • Dynamic pressures • Flow rates • System dispersions • Wind dispersions ••• Air inlet ••• Derived air volume ••• Mach transitions		• Antennae range data		• Launch mission rules
3		• Air loads on propulsion elements •• Engine installed thrust ••• Forebody pressure recovery and flow field definition history	• Aerothermal test requirements	• Plume electron profiles • Ascent and descent pressure profile • Heating and pressure instrumentation requirements	• Ascent and descent pressure profile	
4		• Structural analysis of lines and brackets • Establish dynamic envelop of feedline • Determine line thickness ••• Aft and forebody structures	• Loads • Life limit	• Vibro-acoustical requirements	• Vibro-acoustical requirements • Review of battery cell design (pressure vessel)	• Transportation loads
5	• Thermal protection system sizing (aerothermal and base heating) • Cryogenic insulation sizing • Active thermal control system sizing • Component weight estimates • Parts list	• Propellant condition • Temperature time history • Pressure • Childown of engine • Temperatures and heating loads	• Structural temperature requirements	• Thermal environment	• Thermal environment for EPS • Power requirements for thermal control systems	• Structural temperature requirements
6		• POGO suppressor requirements • TVC requirements • RCS requirements		• Software requirements • Computer requirements • Sensor requirements	• Power requirements for control system	
7	3.7 Mass Properties	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia	• Documented control weights • Weights • Centers of gravity • Moments of inertia	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia	• Mass properties control plan • Documented control weights • Weights • Centers of gravity • Moments of inertia	
8	• Propulsion system drawings and models • Component weight estimates • Parts list	3.8 Propulsion	• Environments • Loads • Life limits	• Instrumentation • Uplink and downlink requirements • Drive electronics • Thrust vector control requirements	• Electrical power requirements	• MPS checkout and fill • Refurbishment and inspection requirements • Hardware design • Verification requirements • Transportation requirements

	M	N	O	P	Q	Products
External Inputs	• Project groundrules • Design-to-cost goals • Critical interfaces • Environmental operations constraints • Range safety constraints	• Project groundrules • Design-to-cost goals • EPA and OSHA constraints	• Project groundrules • Design-to-cost goals • EPA and OSHA constraints	• Project groundrules • Design-to-cost goals • Operations concept • Historical data • Reliability requirement	• Project groundrules • Design-to-cost goals • Work breakdown structure • Schedule • Technology requirements • Reliability	
Natural Environment Inputs			• Severe weather • Lightning			• Electro-mechanical effects plan
1	• System definition and design description document • Holddown and release mechanism • Vehicle coordinate system	• Drawings	• Drawings • Hazard analysis inputs	• System definition and design description • Schematics • Failure mode effects analysis inputs ••• Critical items list inputs	• Vehicle configuration • Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan inputs • Type of construction	• Layouts • Three dimensional models • Detail drawings • Center of gravity locations • Cross-section properties
2	• Burn times • Jettison times • Loads trajectory data • Vehicle breakup and disposal analysis • Launch Commit criteria • Launch corridor •• Landing corridor		• Dispersion • Abort alternate mission analyses	• Event timelines		• Payload and performance • Trajectory parameters • Ground track • Impact points • Dispersion • Abort alternate mission analyses
3			• Sonic boom overpressure	• Environment and loads definition	• Test requirements to include instrumentation	• Vehicle aerodynamics • Aerothermal (ascent and re-entry aero and plume heating) • External acoustics • Launch stand heating and pressures • Compartment pressures • Test requirements
4			• Structural failure modes • Failure propagation logic development • Structural design analysis	• Structural failure modes • Failure propagation logic development • Structural design analysis	• Test requirements to include instrumentation	• Stress analysis • Fracture and fatigue assessment • Design loads • Structural dynamic models and analyses • Test requirements and support: strength, modal survey, acoustical and random vibrations, shock
5	• Subsystem definition and design description document			• Environments and loads definition	• Material type • Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan	• Thermal protection system sizing • Cryogenic insulation sizing • Compartment purge and conditioning analysis • Active thermal control system sizing • Test requirements
6			• Diagnostics and control logic	• Diagnostics and control logic	• Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan	• Stability margins • Baseline autopilot configuration • Guidance algorithms • Test requirements
7	• Documented control weights • Weights • Centers of gravity • Moments of inertia				• Vehicle weights by work breakdown structure • Quantities	• Mass properties control plan • Periodical mass properties reports - weight - centers of gravity - moments of inertia
8	• Subsystem definition and design description document • Vehicle controls • Power usage ••• Flight rules	• Drawings	• Drawings • Schematics • Hazard analysis inputs	• Functional failure modes • Failure propagation logic development • Diagnostics and control logic • Failure mode effects analysis inputs ••• Critical items list inputs	• Technical descriptions • Vendor quotes • Test requirements to include instrumentation • Production quantities • Make or buy plan	• Propellant inventory • MPS design • Tank fill, drain, pressure profile • MPS analysis • Press models • Propellant conditioning models • Steady state models • Test analysis support • TVC system design • Test requirements

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 1b. N×N diagram, bottom partition.

Outputs →

Inputs	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	Products
9	• Material allowables ••• Material selection consultation ••• TPS ••• Material thermal (required and expected)			• Material properties • Material allowables ••• Material selection consultation ••• TPS ••• Material thermal (required and expected)	• Material properties • Material allowables ••• Material selection consultation ••• TPS ••• Material thermal (required and expected)		• Material mass density	• Material compatibility • Contamination analysis • Material properties • Thermal and cryogenic properties • Temperature limits	3.9 Materials	• Materials properties	• Materials properties	• NDE plan • Contamination control plan		• Material and process control plan • NDE plan • Contamination control plan • MIUL and MUA	• Material certifications	• Materials definition • Structural design analysis support	• Material properties • Material costs	• Material and process control plan • NDE plan • Contamination control plan • MIUL and MUA
10	• Packaging volume required	• Antennae types and locations			• Thermal design limits • Sensor characteristics	• Sensor characteristics • Computational characteristics • Antenna types and locations	• Control and data management system drawings and models • Component weight estimates • Parts list	• Telemetry capability • Sensor characteristics		3.10 Communications and Data Handling	• Black box interfaces for cable harness design • Power requirement for control and data management boxes	• Hardware design • Verification requirements • Transportation requirements	• Commands and telemetry uplink and downlink database • Subsystem definition and design description document • Instrumentation - software design - power usage		• Hazard analysis inputs	• Design configuration • Reliability data • Failure mode effects analysis inputs ••• Critical items list inputs	• Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan	• Range safety • Flight computer • Data handling • Instrumentation • Software • Link margin
11	• EPS component details • Packaging volume required				• EPS operational environment requirements		• Electrical system drawings and models • Component weight estimates • Parts list	• Availability of power (current, voltage, phase) • Budget		• Power characteristics • Instrumentation requirements	3.11 Electrical Power		• Power system constraints • Subsystem definition and design description document		• Hazard analysis inputs	• Design configuration • Reliability data • Failure mode effects analysis inputs ••• Critical items list inputs	• Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan	• EPS design • Cable harness design • Cable interconnect diagram • Electrical systems schematics • EGSE design • Power distributor design
12	• Ground interface • Access requirements ••• Turnaround, launch, and landing facilities			• Drawings for flight ground support equipment				• Operational timelines • Maintainability • Ground support equipment capability		• Instrumentation and command requirements • Processing requirements	• Identify need for EGSE for integrated checkout	3.12 Ground Operations	• Ground test and checkout procedures • Ground support equipment design and definitions	• Drawings for flight ground support equipment			• Ground support equipment technical descriptions • Ground test requirements • Operational timelines • Crew sizes • Facility requirements • Software requirements	• MGSE design • Integration and test plan • Transportation and logistics plan • Ground operations plan and processing flows • Launch site support requirements • Test and checkout requirements • Detailed test and checkout procedures • Operations and maintenance manuals
13	• Vehicle integrated operations concept and requirements • On-orbit flight operations •• Landing gear	• Launch commit criteria • Launch corridor •• Landing corridor	• Vehicle integrated operations concept and requirements	• Launch sequence timelines • Vehicle integrated operations concept and requirements • Flight mission reserve and launch mission reserve	• Vehicle integrated operations concept and requirements			• Vehicle integrated operations concept and requirements • Flight timeline	• Vehicle integrated operations concept and requirements	• Launch sequence timeline • Flight sequence timeline • Operations health and status requirements • Flight load tanle updates (trajectory) • Performance requirements for mission • Vehicle integrated operations concept and requirements	• Launch sequence timeline • Flight sequence timeline • Vehicle integrated operations concept and requirements	• MST level 4 test requirements • Level 1 requirements • Human factors and operability assessment - ground operations - flight operations • Vehicle integrated operations concept and requirements • Launch sequence timeline	3.13 Flight Operations		• Vehicle integrated operations concept and requirements		• Integrated operations concept • Flight rest requirements • Operational timelines • Crew sizes • Facility requirements • Software requirements	• Launch sequence procedures • Data flow analysis timeline • Ground command loads
14	• Fabrication parameters							• Fabrication parameters	• Manufacturing control plan • Assembly and verification plan • Make or buy plan	• Review of avionics packaging documentation	• Review of avionics packaging documentation			3.14 Manufacturing		• Input to failure propagation logic	• Facility and tooling requirements • Manufacturing cost	• Flight vehicle • Flight ground support equipment
15	• Range safety requirements • Hazard analysis • Fault tolerance requirements	• Range safety requirements • Hazard analysis • Fault tolerance requirements	• Hazard analysis	• Hazard analysis • Fault tolerance requirements	• Hazard analysis • Fault tolerance requirements	• Hazard analysis • Fault tolerance requirements		• Flight safety review of schematic and operations • East and west test range interface to assure compliance • Hazard analysis • Fault tolerance requirements	• Hazard analysis	• Hazard analysis • Fault tolerance requirements	• Hazard analysis • Fault tolerance requirements	• Hazard analysis • Fault tolerance requirements	• Safety constraints and guidelines • Vehicle and launch facility FMEA • Hazard analysis	• Quality control plan • Hazard analysis	3.15 Safety			• Quality assurance plan • Hazard analysis reports • Failure mode and effects analysis • Critical items list
16	• Reliability estimates • Trade support • Failure mode effects analysis inputs ••• Critical items list inputs • System-to-subsystem reliability allocations	• Failure mode effects analysis inputs • Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs	• System and component reliability allocation and estimation • Failure mode effects analysis inputs ••• Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs		• Reliability allocation and estimation • Failure mode effects analysis inputs ••• Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs • System-to-subsystem reliability allocations	• Reliability estimates	• Reliability estimates • Failure mode effects analysis inputs ••• Critical items list inputs	• Reliability inputs to operations model • Failure mode effects analysis inputs ••• Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs	• Failure mode effects analysis inputs ••• Critical items list inputs	• Reliability model	3.16 Reliability	• Vehicle reliability • Requirements and estimates	• Reliability allocations and estimates • Integrated risk analysis • Test input • Trade support • Alert process • PRACA system
17	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades • Procurement support	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Hardware design, development, testing, evaluation and production costs • Cost trades	• Ground support equipment design, development, testing, evaluation and production costs • Operations costs • Costs trades	• Operations costs • Costs trades	• Facility and tooling design, development, testing, evaluation and production costs • Cost trades		• Cost goals, requirements and constraints	3.17 Cost	• Cost trades • Work breakdown structure • Groundrules and assumptions • Program cost estimate • Commercial vehicle business analysis and plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

2.1.2 Process Flow Diagrams

Figures 3–19 describe, at a first level, the process flow within each design discipline. They also indicate the information flow between the interfacing disciplines. The common generic activities and formal report products are also described in these figures.

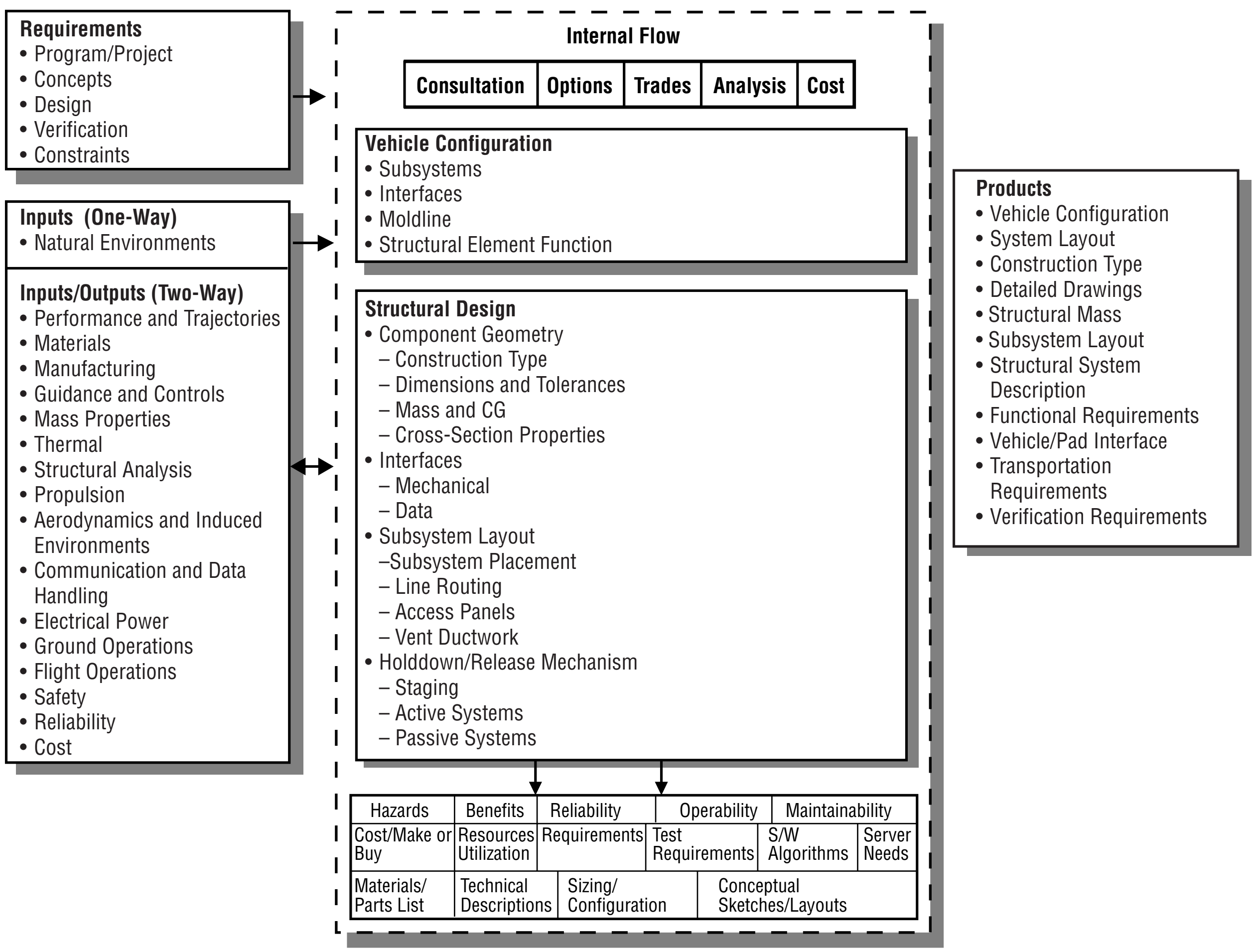


Figure 3. WBS 2.1, Vehicle configuration and structural design process flow diagram.

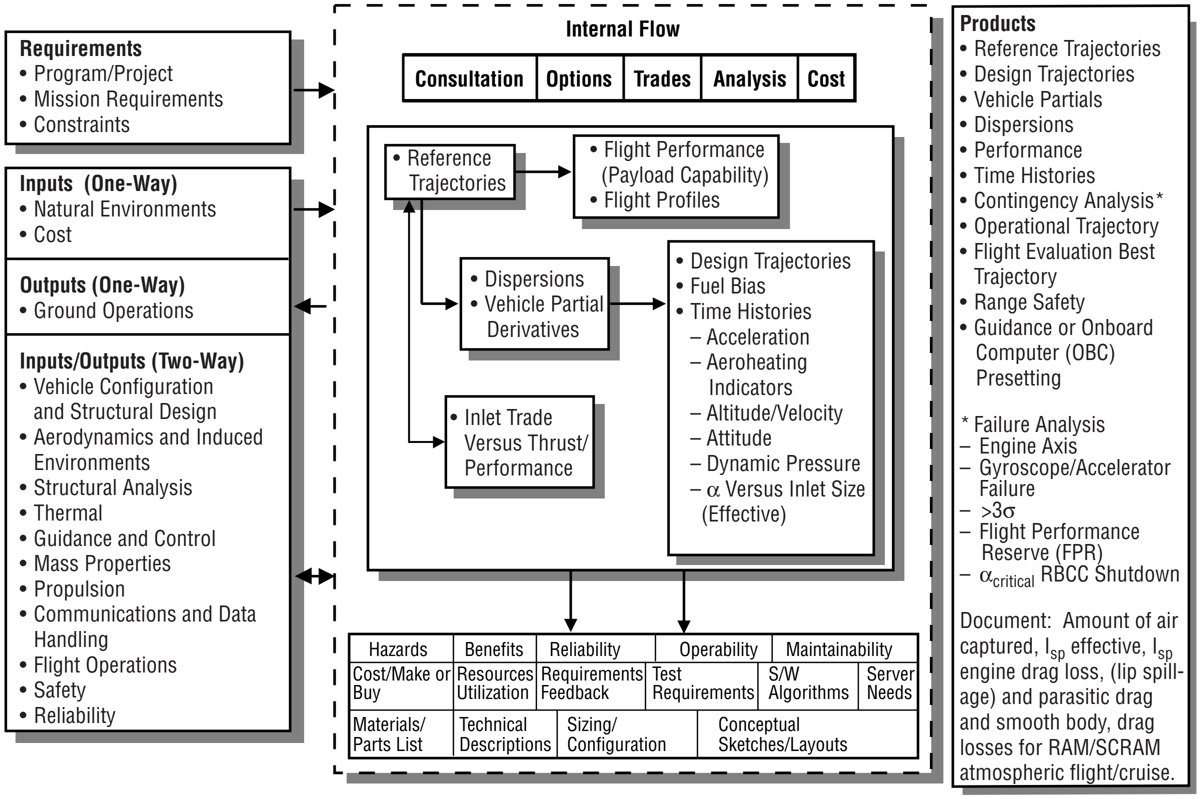


Figure 4. WBS 2.2, Performance and trajectories design process flow.

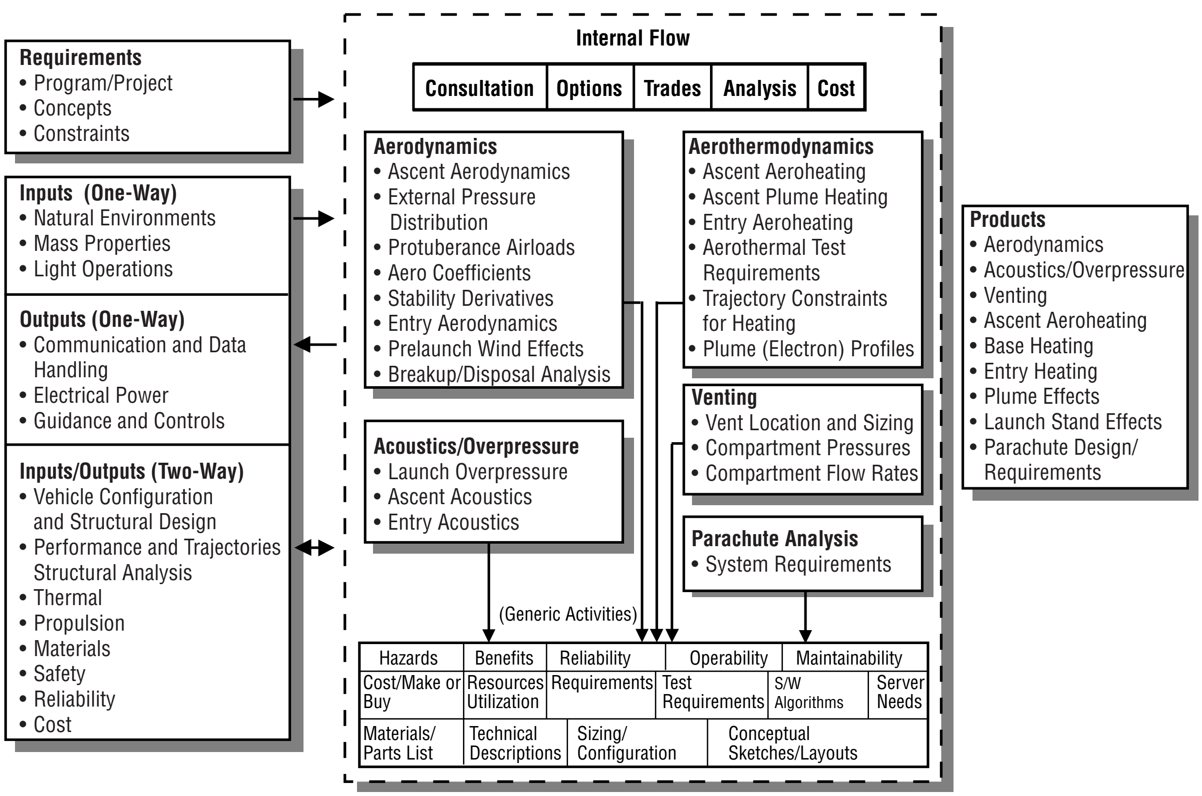


Figure 5. WBS 2.3, Aerodynamics and induced environments design process flow.

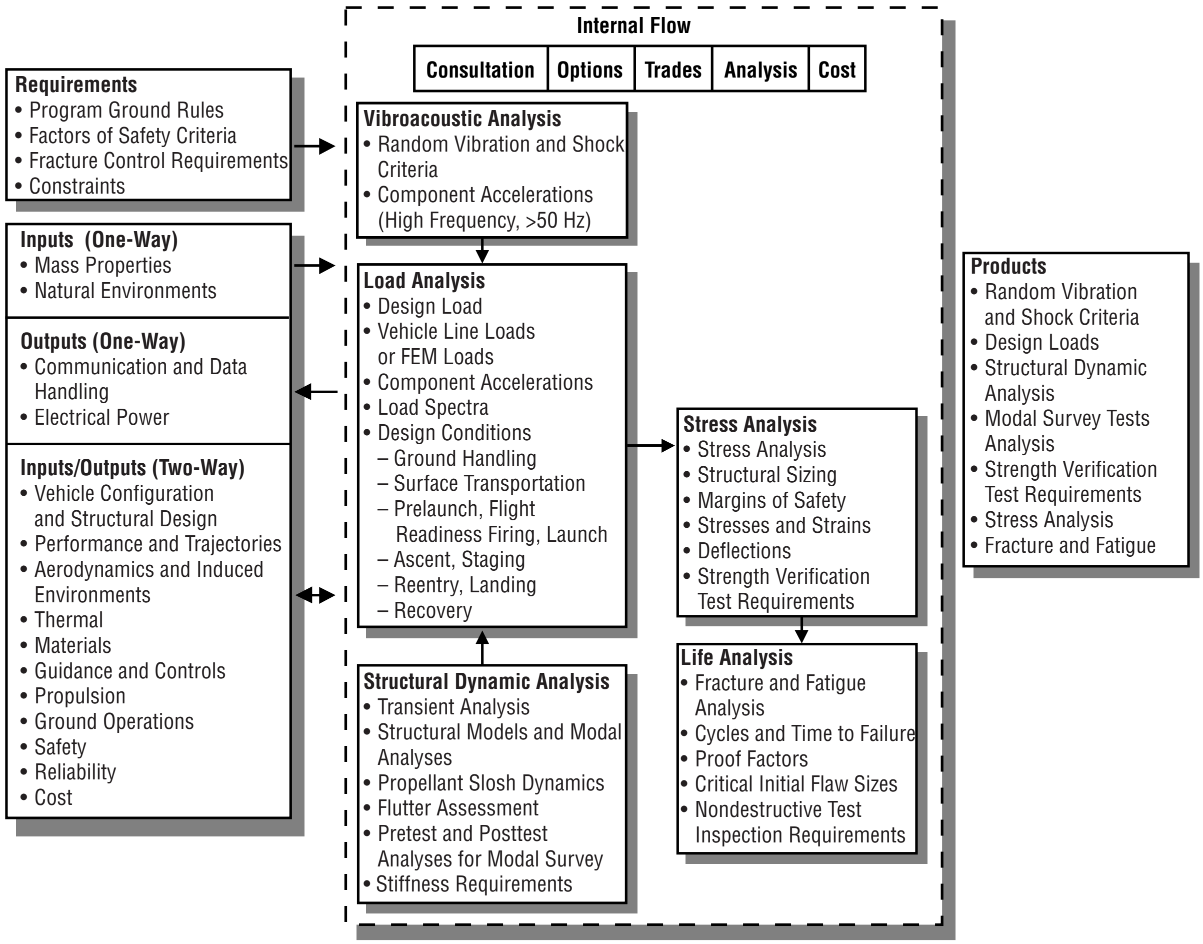


Figure 6. WBS 2.4, Structural analysis design process flow.

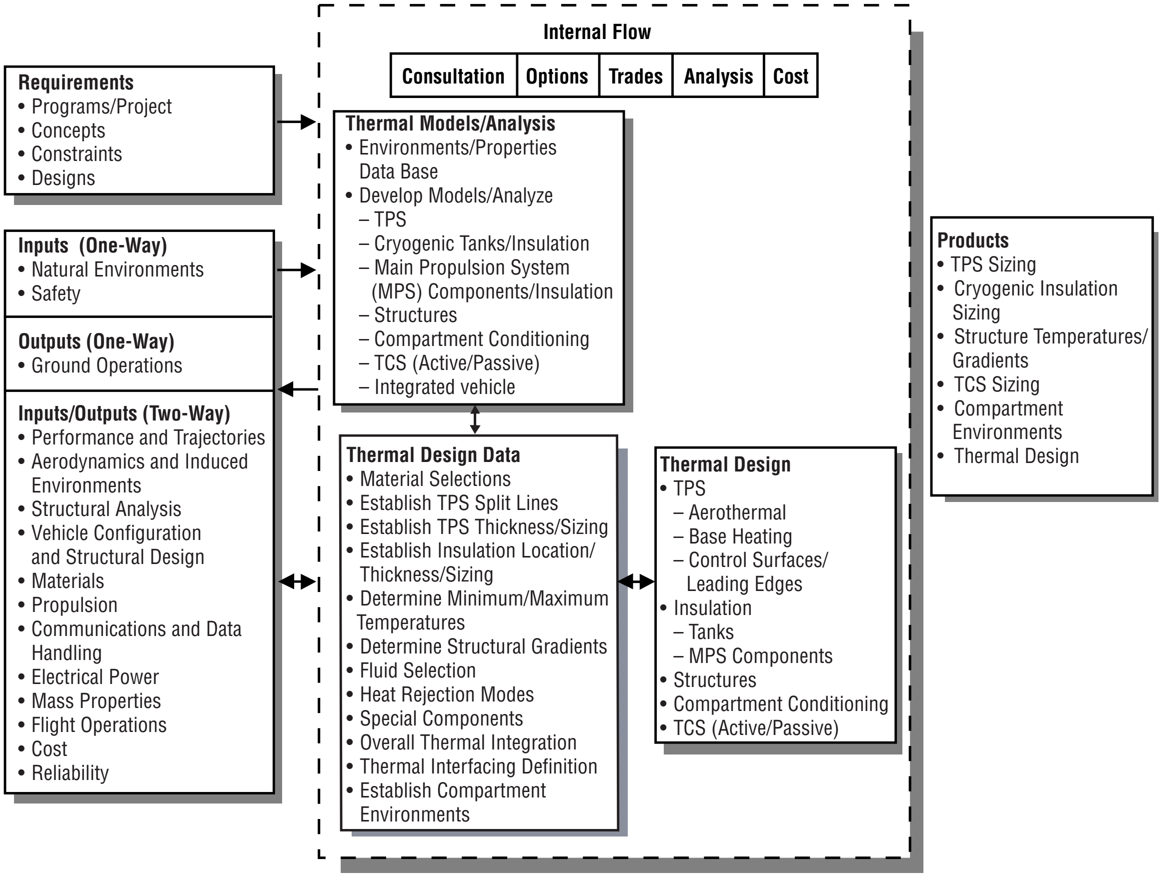


Figure 7. WBS 2.5, Thermal design process flow.

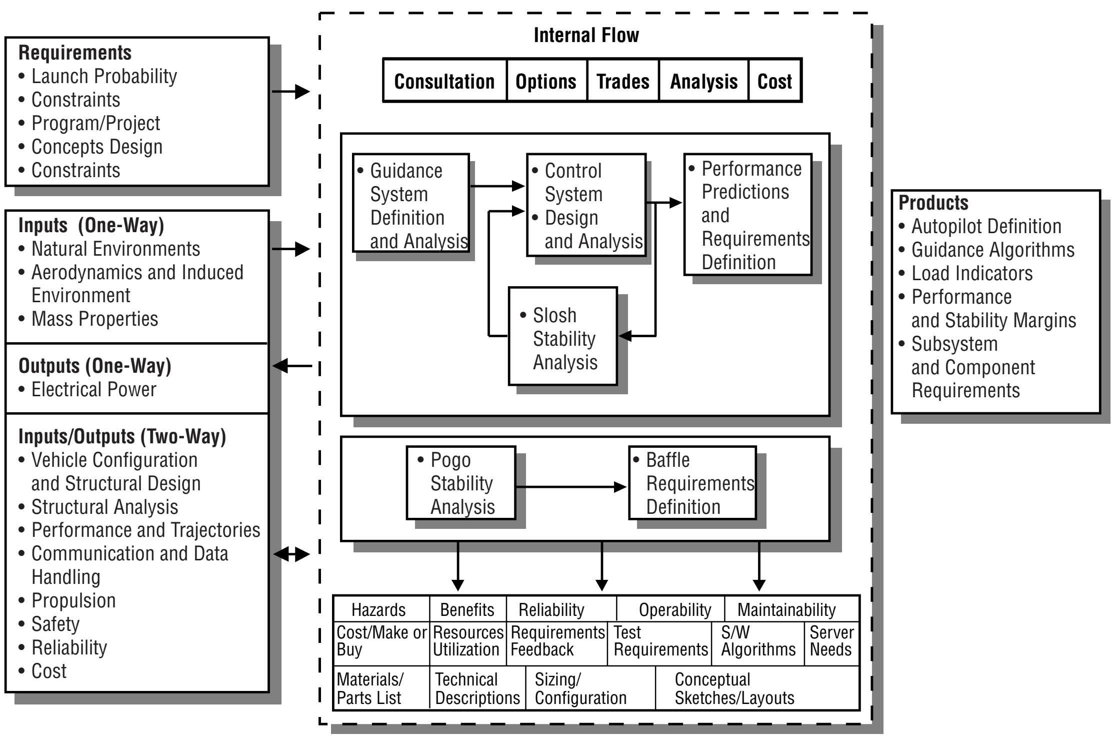


Figure 8. WBS 2.6, Guidance and control design process flow.

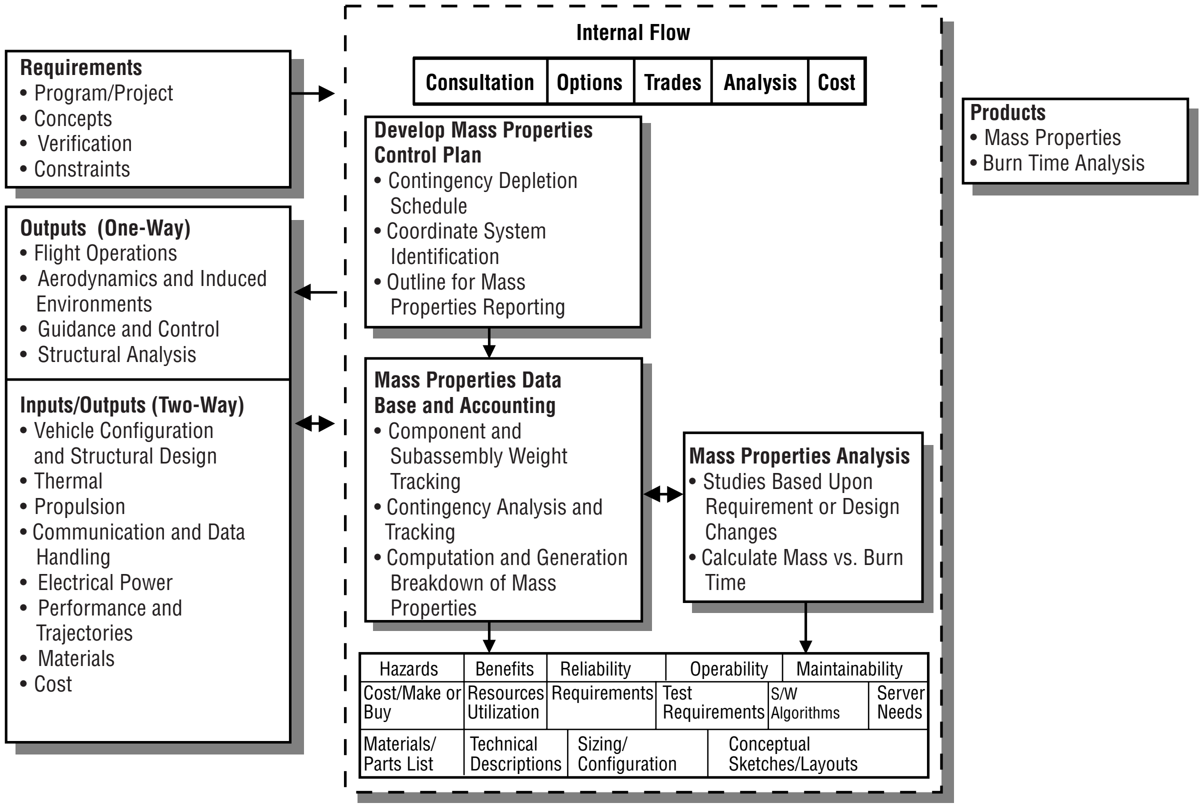


Figure 9. WBS 2.7, Mass properties design process flow.

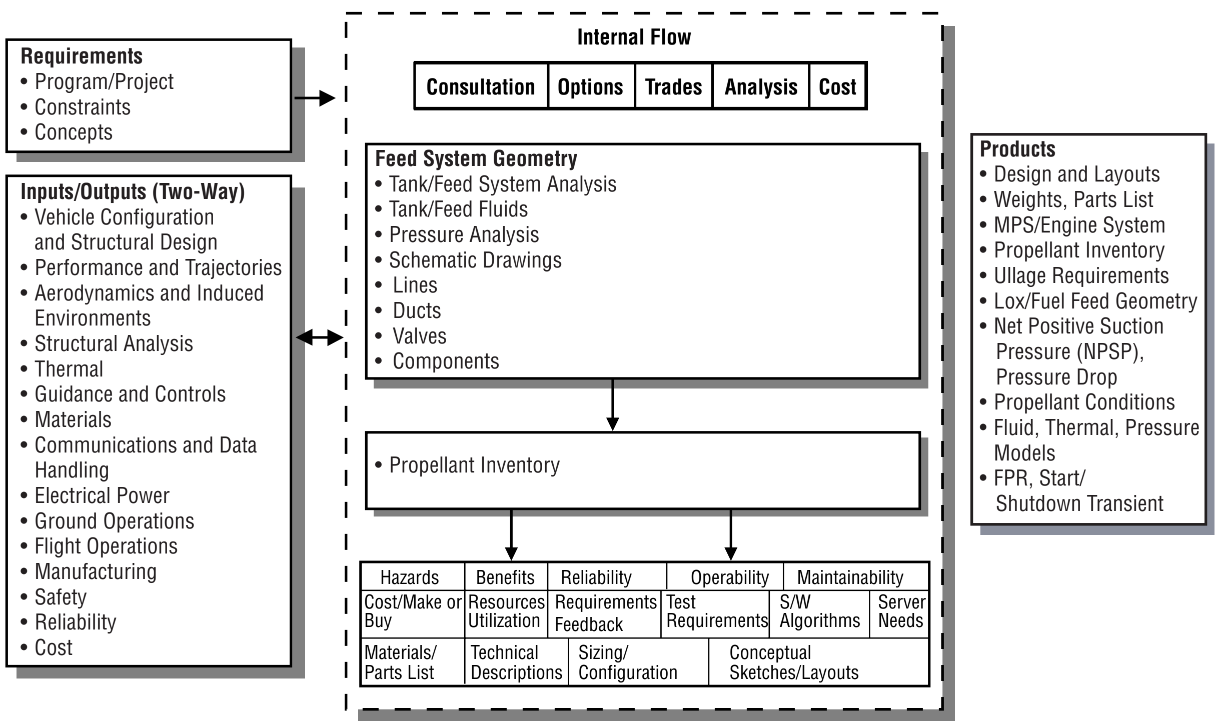


Figure 10. WBS 2.8, Propulsion systems design process flow.

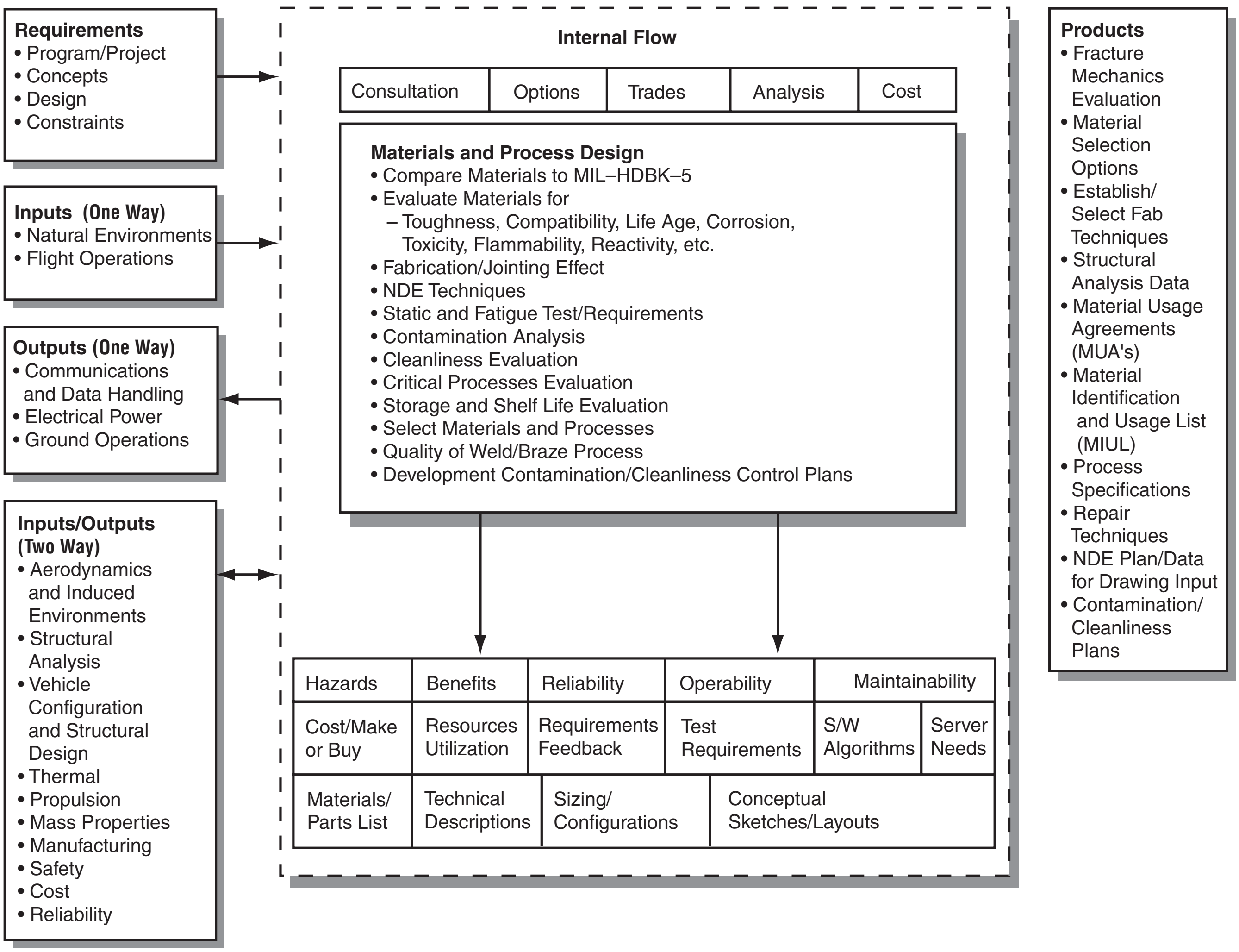


Figure 11. WBS 2.9, Materials and processes design process flow.

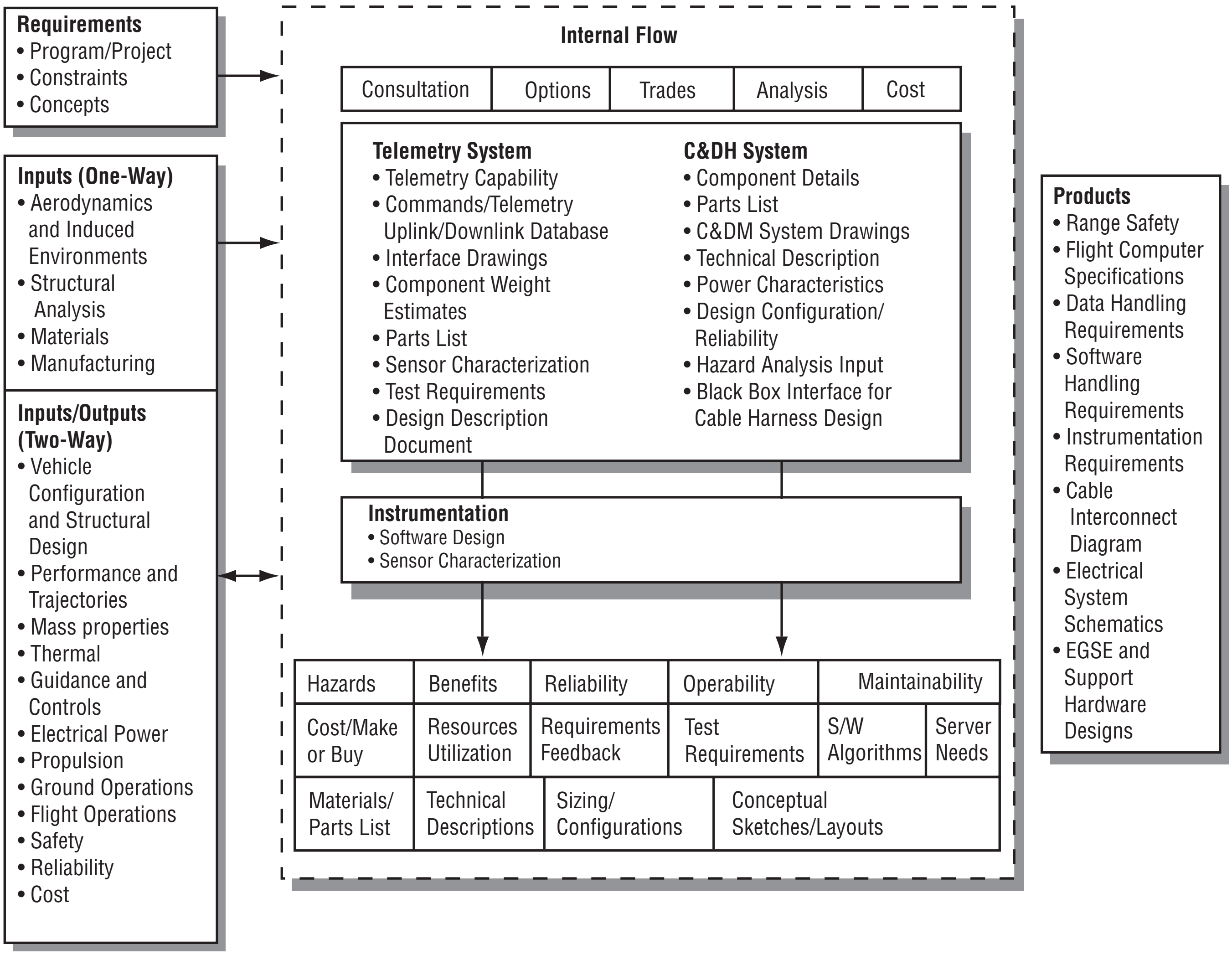


Figure 12. WBS 2.10, Communications and data handling design process flow.

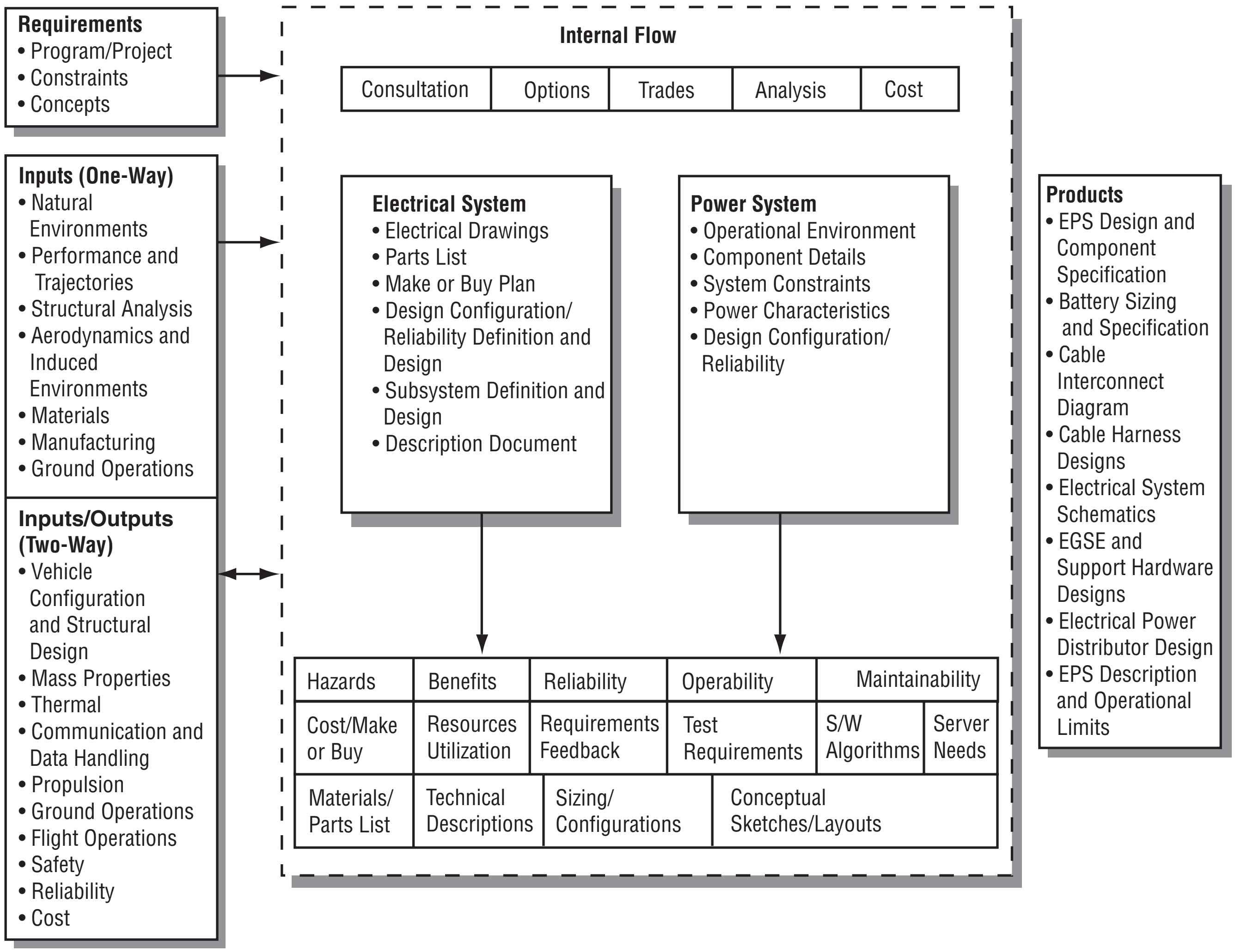


Figure 13. WBS 2.11, Electrical power design process flow.

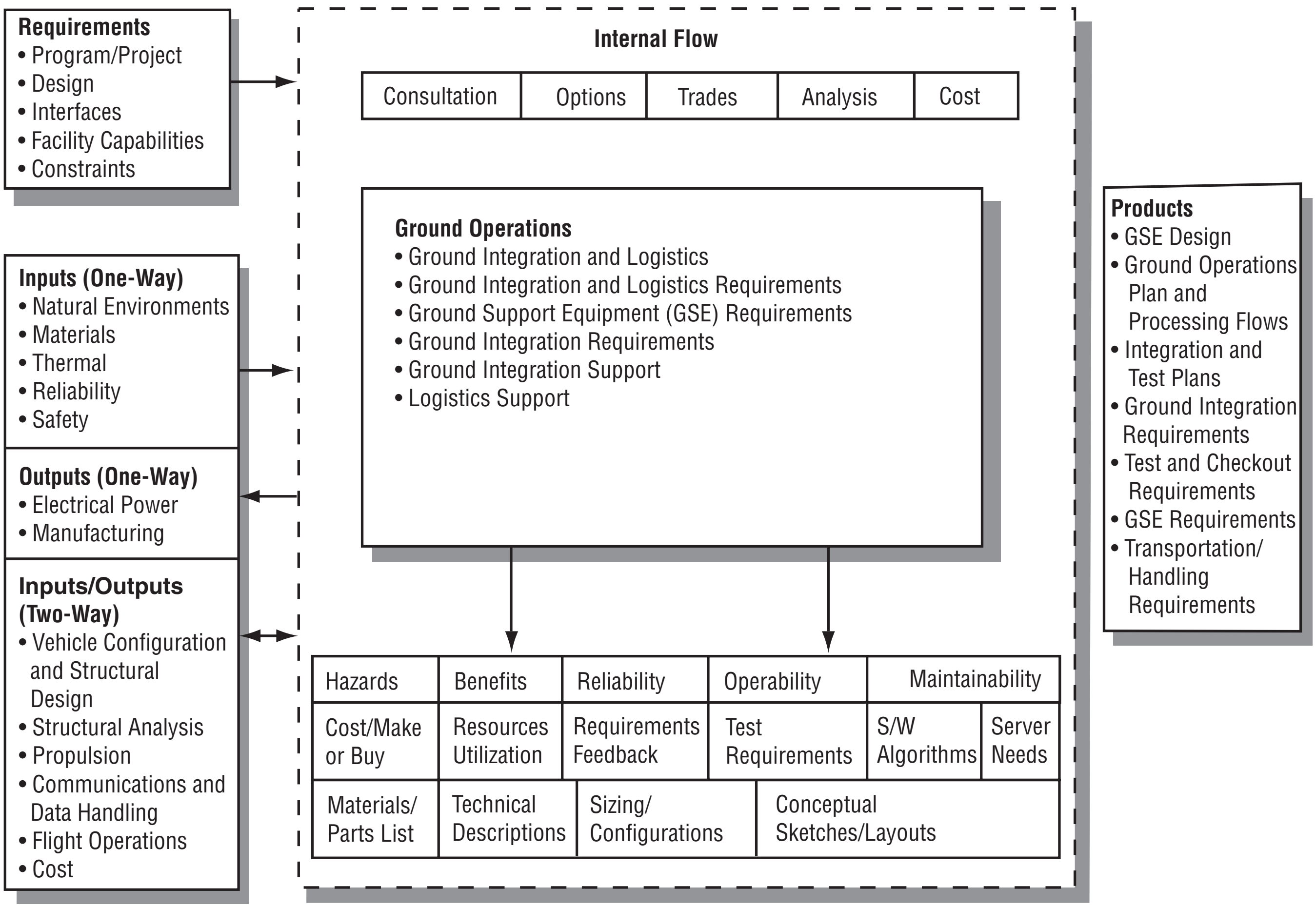


Figure 14. WBS 2.12, Ground operations design process flow.

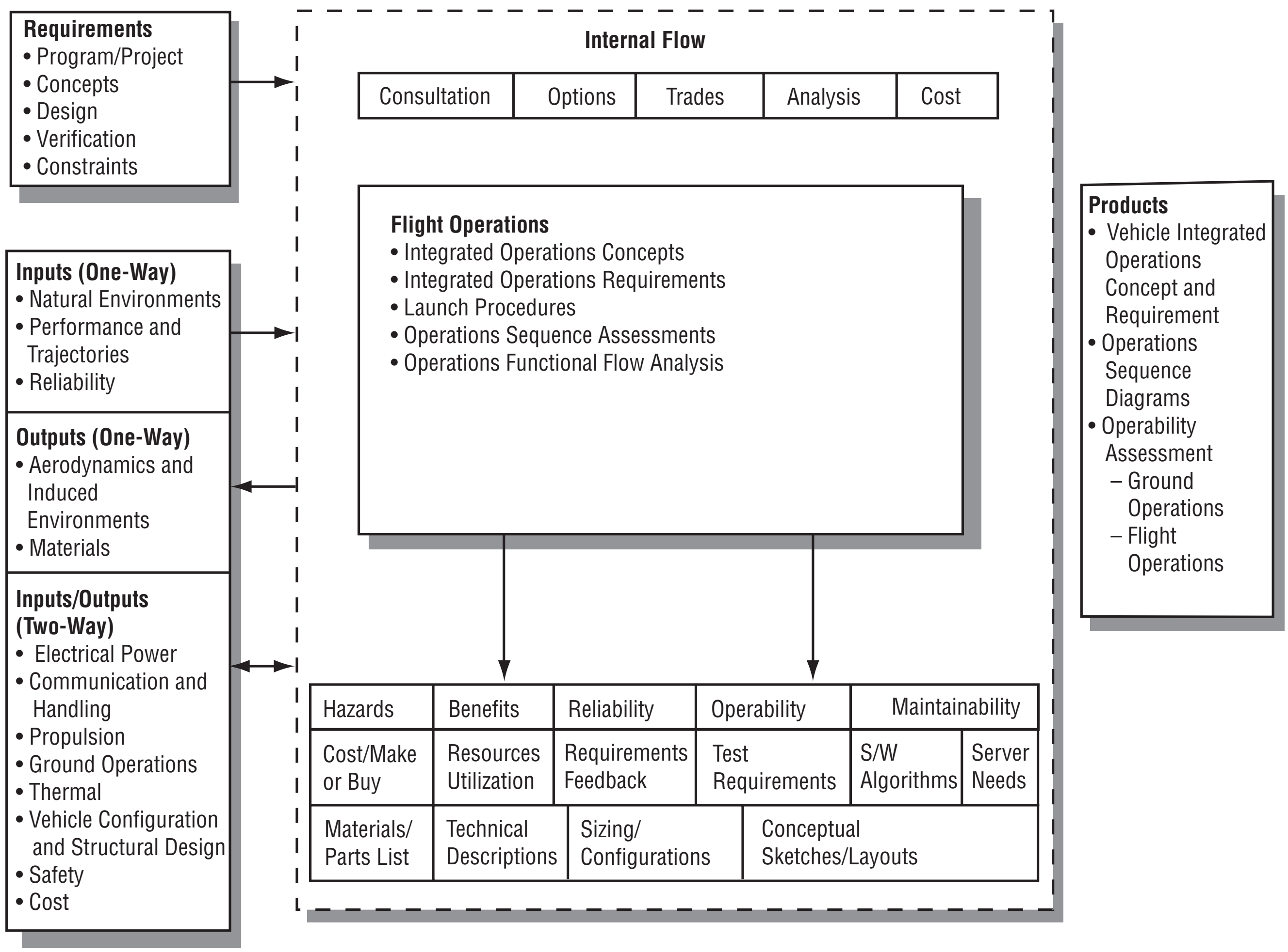


Figure 15. WBS 2.13, Flight operations design process flow.

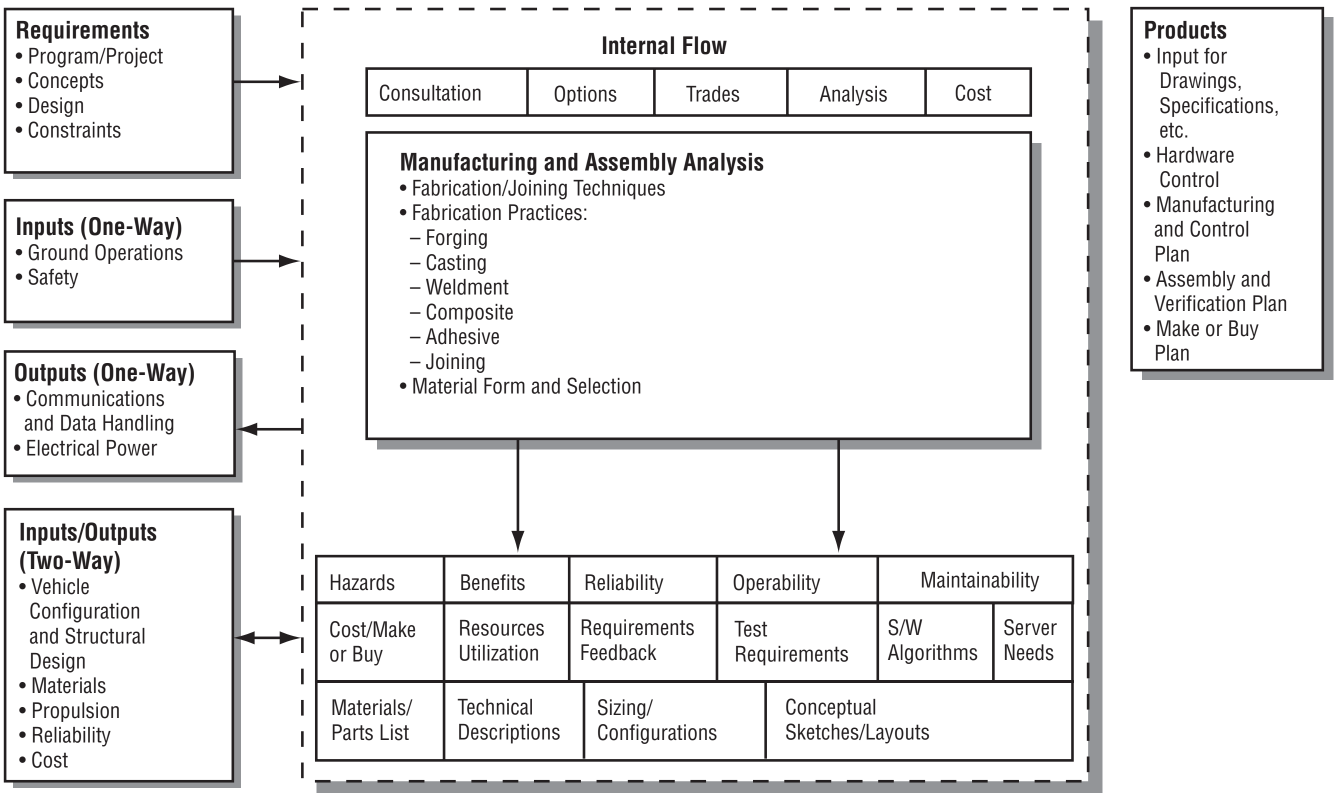


Figure 16. WBS 2.14, Manufacturing design process flow.

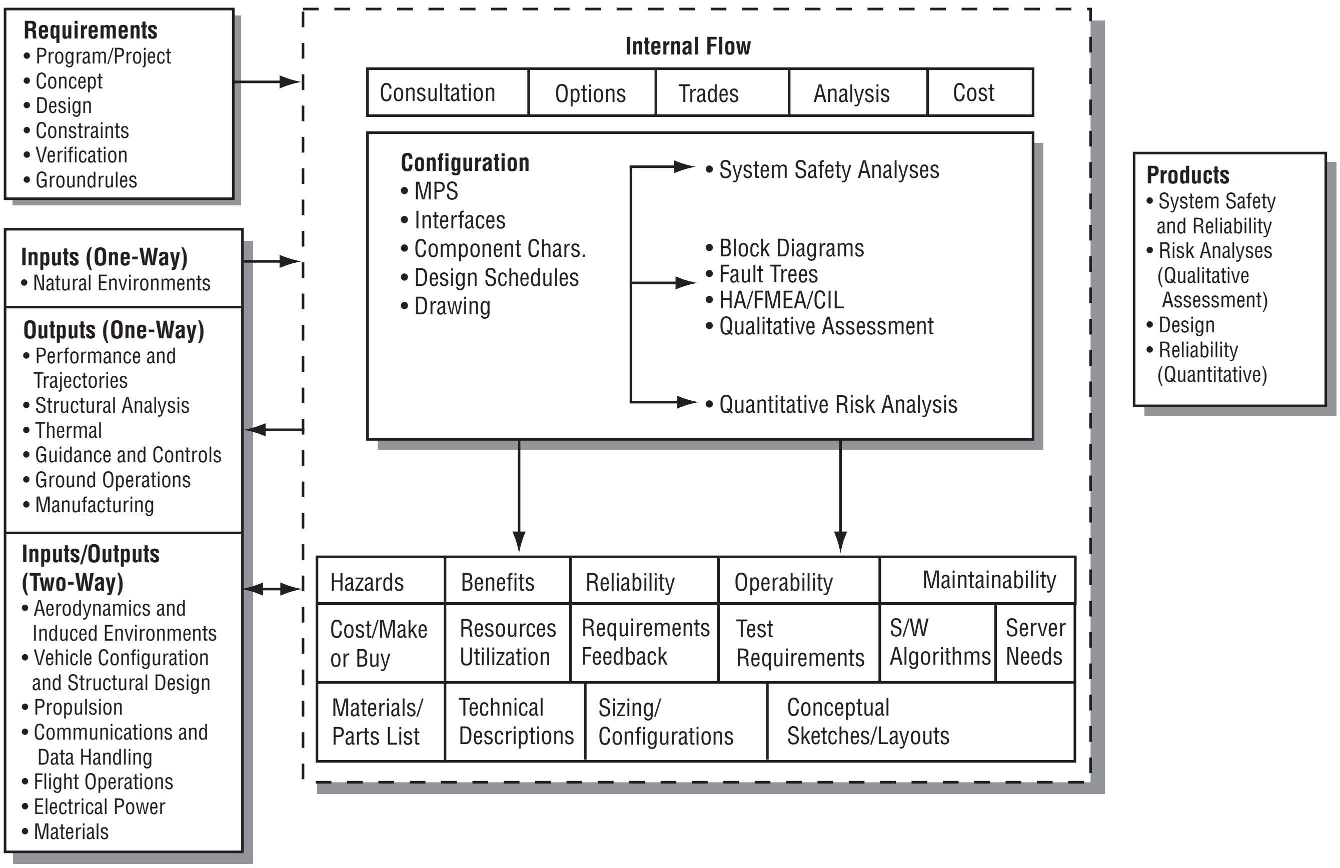


Figure 17. WBS 2.15, Safety design process flow.

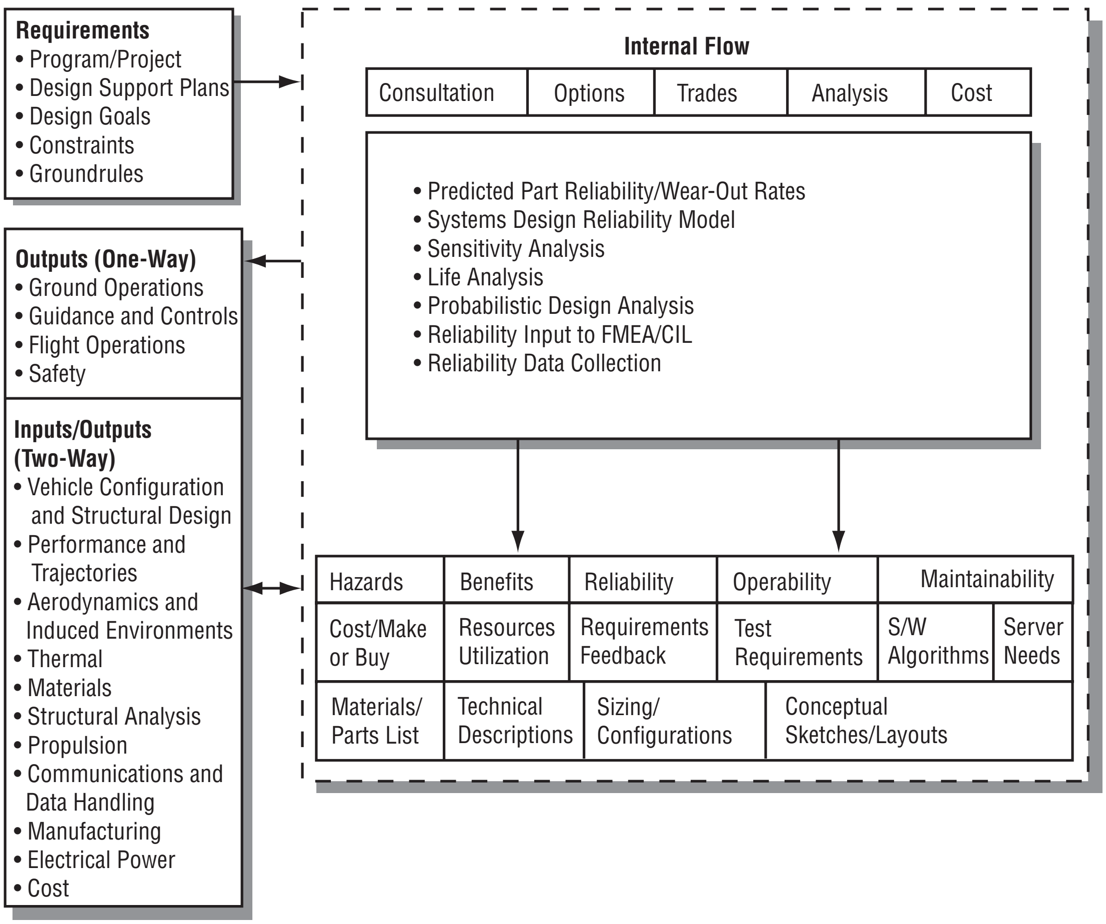


Figure 18. WBS 2.16, Reliability design process flow.

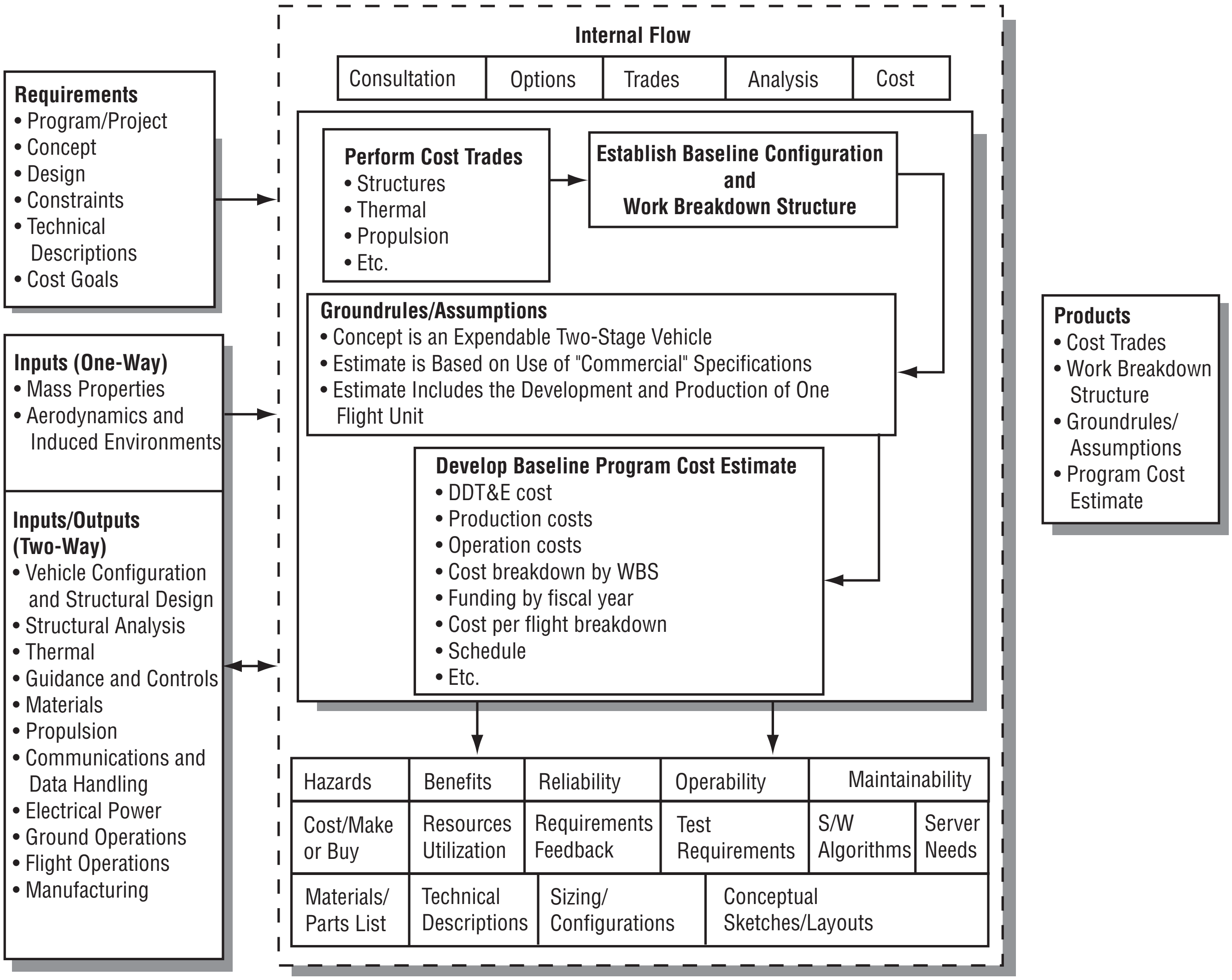


Figure 19. WBS 2.17, Cost design process flow.

2.1.3 Task Descriptions

Tables 2–18 describe, at a first level, the tasks required of each design discipline. These tables provide a “shopping list” of tasks for each discipline or function. The input information items required to accomplish the tasks and the output information items produced by the tasks are listed. These tables also uniquely list the software tools used to accomplish the tasks.

Table 2. Task description, WBS 2.1, Vehicle configuration and structural design.

Inputs	Tasks	Outputs
• Projected ground rules and goals • Production and ground operations • Critical interfaces • Subsystems definitions • EPA and OSHA constraints • Environmental operations constraints • Preliminary design concept and databases • Staging requirements • Propellant requirements •• Entry propellant weight • Pressure vent sizes and locations • Structural sizing and margins of safety • Loads and deflections • Propellant slosh baffle sizing • Cryogenic insulation sizing • Active thermal control system sizing • Temperature and propellant sensor locations • Maximum engine deflection • Control sensor locations • Control surface deflection requirements • Mass properties data—weight; e.g., inertias • Propellant inventory • Propulsion system layout • Tank internal pressures ••• Forebody moldline (iterate required air volume) ••• Staging requirements ••• Propellant requirements • Material allowables ••• Material selection consultation ••• TPS design, thermal materials required • Packaging volumes required • Electrical power system (EPS) component details • Access requirements ••• Turnaround, launch, and landing facilities • Vehicle integrated operations concept and requirements • On-orbit flight operations •• Landing gear drawings • Fabrication parameters • Range safety requirements • Hazard analysis • Fault tolerance requirements • Reliability estimates • Failure mode effects analysis inputs ••• Critical items list (CIL) inputs • System-to-subsystem reliability, allocations hardware design, development, testing, evaluation, and production costs • Cost trades	3.1.1 Configure vehicle 3.1.2 Layout three-dimensional structural model 3.1.3 Determine suitable construction type (e.g., truss, isogrid, etc.) 3.1.4 Select appropriate material 3.1.5 Calculate structural member sizes 3.1.6 Analyze cross-section moments of inertia 3.1.7 Determine structural component mass and CG location 3.1.8 Assess provisions for clearance and access 3.1.9 Locate subsystems 3.1.10 Route subsystem lines 3.1.11 Produce detail drawing for manufacturing shop 3.1.12 Design structural components 3.1.13 Identify shock sources 3.1.14 Specify critical dimensions 3.1.15 Establish suitable manufacturing tolerances Tools: • Commercial software—CAD platform and translators, EMS • In-house software—optimization design codes	• Engine alignment tolerances • Vehicle geometry and structural details • Feedline drawings • Component weight estimates • Parts list • Cross-sectional properties • Line routing zones • Pressurant bottle locations ••• Preliminary air column ••• Profile • Power return thru structure • Component installation • Verification requirements • Transportation requirements • System definition and design description document • Holddown release mechanism • Hazard analysis inputs • Schematics • Failure mode effects analysis inputs ••• Critical items list (CIL) inputs • Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan inputs

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 3. Task description, WBS 2.2, Vehicle performance and trajectories.

Inputs	Tasks	Outputs
• Mission definitions • Initial performance • Vehicle coordination system • Launch pad geometry • Project ground rules and goals • Redundancy requests • Preliminary design concept and database • Range safety constraints • Atmospheric model • Ascent wind models • Launch pad environments • Engine alignment tolerances ••• Vehicle geometry drawing • Vehicle ascent aerodynamics • Heating indicators •• Vehicle/stage entry aerodynamics • Engine inlet flow field definition • Engine installed thrust throughout trajectory • $Q\alpha$, $Q\beta$ constraints and structural load indicators •• Wall/surface temperatures • Heating rate or temperature indicators • Autopilot definition • Guidance system inputs ••• Modified autopilot to reflect a control law for airflow to inlet • Control surface mixing logic • Control weights and current weights	3.2.1 Perform trade studies on trajectory/configuration options 3.2.2 Develop nominal trajectories 3.2.3 Develop design trajectories 3.2.4 Assess vehicle sizing, mass properties 3.2.5 Evaluate vehicle performance 3.2.6 Develop abort scenarios and trajectories Tools: • Software—Dynamic simulations, program to optimize simulated trajectories (POST)	• Staging requirements • Propellant requirements • Number of engines • Performance updates • Entry propellant weight • Ascent trajectory sets (altitude, velocity, X, β histories) and engine operating conditions •• Entry trajectories ••• Airflow history to inlet • Trajectory constraints ••• Mach transitions • Loads trajectory data ••• Ascent, cruise, loading requirements • Reference trajectories and time histories • Max Q ••• α, airflow ••• Ascent, cruise, landing requirements • Propellant load versus time • Burn times • Residuals at main engine cutoff, etc. • Vehicle mass versus time • I_{sp} (flow rates) • Usable propellant requirements • Flow rates • System dispersions ••• α inlet ••• Derived air volume • Antenna range data • Launch mission rules • Vehicle breakup and disposal analysis • Launch commit criteria • Launch corridor ••• Landing corridor • Abort alternate mission analyses • Event timelines

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 4. Task description, WBS 2.3, Aerodynamics and induced environments.

Inputs	Tasks	Outputs
• Project ground rules and goals • Launch pad geometry • Preliminary design outer moldline • Ground and ascent wind profiles • Atmospheric models • Launch stand ambient temperatures • Protuberance geometry • Engine placement geometry • Ascent trajectory sets (altitude, velocity, α, β histories) and engine operating conditions • Entry trajectories ••• Airflow history to inlet • Trajectory constraints ••• Mach transitions • Structural deflections • Heating constraints •• Wall/surface temperatures • Control weights, centers of gravity • Engine dimensional and operational characteristics • Turbine exhaust definition • On-pad effluent definition ••• Rocket-based combined launch (RBCC) exhaust conditions ••• Forebody inlet performance requirements ••• Transition mach number • Vehicle integrated operation concept and requirements • Hazard analysis • Failure mode effects analysis inputs ••• CIL inputs	3.3.1 Aero design consultation 3.3.2 Generate ascent aerodynamics 3.3.3 Generate external pressure distributions 3.3.4 Generate protuberance airloads 3.3.5 Generate aero coefficients 3.3.6 Generate aero stability derivatives 3.3.7 Generate vehicle/stage entry aerodynamics 3.3.8 Determine vent size and location requirements 3.3.9 Determine compartment pressures 3.3.10 Calculate compartment flow rates 3.3.11 Generate ascent aeroheating histories 3.3.12 Generate ascent plume heating histories 3.3.13 Generate entry heating histories 3.3.14 Determine aerothermal test requirements 3.3.15 Specify trajectory constraints for heating 3.3.16 Generate launch overpressure environments 3.3.17 Generate ascent acoustics environments 3.3.18 Generate entry acoustics environments 3.3.19 Determine prelaunch wind effects 3.3.20 Determine parachute system requirements 3.3.21 Perform breakup/disposal analysis 3.3.22 Generate plume electron profiles Tools: • Computer codes: CEC/TRAN72, SPF/2, SIRRM, RAMP2, RAVFAC, BLIMPJ, MOC, SPP, LANMIN, MINIVER, Various CFD codes, etc. • Wind tunnel data • Historical ground and flight test database	• Pressure vent sizes and locations • Moldline update including airframe/ engine design • Vehicle ascent aerodynamics • Heating indicators •• Vehicle/stage entry aerodynamics • Engine inlet flowfield definition • External aerodynamic pressure distributions • Compartment pressures • Protuberance airloads • Acoustic/overpressure definition • Fluid dynamic loads (buffeting) • Ascent aero heating histories • Entry aero heating histories • Compartment flow rates • Plume heating environments • Guidance and control instrumentation locations • Air loads on propulsion elements ••• Engine installed thrust ••• Forebody pressure recovery and flow field definition history • Aerothermal test requirements • Plume electron profiles • Ascent and descent pressure distributions • Heating and pressure instrumentation requirements • Sonic boom overpressure • Test requirements to include instrumentation

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 5. Task description, WBS 2.4, Structural analysis.

Inputs	Tasks	Outputs
• Project ground rules and goals • Factors of safety criteria and fracture control requirements • Launch platform finite element model • Ground and ascent wind models • Vehicle geometry • Vehicle/pad interface geometry • Holddown/release mechanism definition • Structural details • Component installations • Shock sources • External aerodynamic pressure distributions • Compartment pressures • Protuberance airloads • Acoustic/overpressure definition • Fluid dynamic loads (buffeting) • Structural temperature and gradients • Slosh damping requirements • Q_α, Q_β envelopes • Flex-body mode frequency constraints • Autopilot definition • Vehicle transient response to wind disturbances • Weights, centers of gravity, moments of inertia • Ignition and shutdown thrust transients, timing • Steady state thrust oscillation • Ullage pressure and tank fill heights versus flight time ••• RBCC exhaust/thrust ••• Forebody inlet • Material properties • Material allowables ••• Material selection consultation ••• TPS design definitions • Material thermal (required/expected) • Drawings for flight GSE • Launch sequence timelines • Vehicle integrated operations concept and requirements • FMR and LMR • Hazard analysis • Fault tolerance requirements • System and component reliability allocation and estimation • Failure mode effects analysis inputs ••• CIL inputs	3.4.1 Vibroacoustic analysis 3.4.2 Load analysis 3.4.3 Structural dynamic analysis 3.4.4 Stress analysis 3.4.5 Life analysis Tools: • Commercial software—NASTRAN, ABAQUS, ANSYS, PATRAN • In-house software—dynamic loads analysis programs, NASGRO, bolt strength analysis software • In-house vibration database	• Structural sizing, margins of safety • Loads and deflections • Propellant slosh baffle sizing • Q_α, Q_β constraints and structural load indicators • Temperature gradient design limits • Vehicle flex-body modes • Propellant slosh modes • Propellant feedline flex modes • Q_α, Q_β and structural load constraints • Structural analysis of lines and brackets • Establish dynamic envelop of feedline ••• Aft/forebody structures •• Life limit • Vibroacoustical design criteria • Review of battery cell design (pressure vessel) • Structural failure modes • Failure propagation logic development • Test requirements to include instrumentation

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 6. Task description, WBS 2.5, Thermal design.

Inputs	Tasks	Outputs
• Project ground rules • Design-to-cost goals • Preliminary design concept and database • Launch pad environments • Configuration details, materials, dimensions ••• Ascent, cruise, loading requirements • Ascent aeroheating histories • Entry aeroheating histories • Compartment flow rates • Plume heating environments • Temperature gradient design limits • Mass properties control plan • Documented control weights • Weights, centers of gravity, moments of inertia • Ground hold conditions • Heat load requirements for propellant conditioning • Chill-down requirements • Engine configuration • Engine operating characteristics • Engine thermal requirements • Material thermal properties • Material allowables ••• Material selection consultation ••• TPS vehicle interface definition ••• Material thermal required • Thermal design limits • Sensor characteristics • EPS operational environment requirements • Vehicle integrated operations concept and requirements • Hazard analysis • Fault tolerance requirements • Failure mode effects analysis inputs ••• CIL inputs • Hardware design, development, testing, evaluation, and production costs • Cost trades	3.5.1 Review phase A results 3.5.2 Establish properties database 3.5.3 Analyze thermal design concepts – TPS – Cryogenic insulation – Compartment thermal assessment – TCS (active/passive) – MPS 3.5.4 TPS sizing 3.5.5 Cryogenic insulation sizing 3.5.6 TCS sizing (active/passive) 3.5.7 Compartment thermal environments 3.5.8 MPS thermal sizing Tools: • Commercial software—SINDA and PATRAN • In-house software	• Temperature sensor locations •• Wall/surface temperatures • Heating rate or temperature indicators • Heating constraints •• Wall/surface temperatures • Structural temperatures and gradients • TPS sizing (aerothermal/base heating) • Cryogenic insulation sizing • Active TCS sizing • Component weight estimates • Parts list • Propellant condition • Temperature time history • Pressure • Chill-down of engine • Temperature and heating loads • Structural temperature requirements • Thermal environment • Thermal environment for EPS • Power requirements for thermal control system • Structural temperature requirements • Subsystem definition and design description document • Environments and loads definition • Materials type • Technical descriptions • Test requirements to include instrumentation • Production quantities • Make or buy plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 7. Task description, WBS 2.6, Guidance and control.

Inputs	Tasks	Outputs
• Project ground rules • Design-to-cost goals • Launch probability requirements • Preliminary design concept and database • Atmospheric model • Wind models (ground/ascent) • Gust models • Launch pad environments • Overall vehicle dimension • Engine alignment tolerance • Feedline drawings • Vehicle aerodynamics • Guidance and control instrumentation locations • Vehicle flex-body modes • Propellant slosh modes • Propellant feedline flex modes • Q_α, Q_β and structural load constraints • Mass properties control plan • Documented control weights • Weights, centers of gravity, moments of inertia • Mass versus time • Thrust vector control (TVC) gimbal capability (degree and rates) • Kinematic analysis • PU system definition ••• Inlet airflow constraints for ascent, cruise, and landing ••• Air capture transition • Sensor characteristics • Computational characteristics • Antenna types and locations • Hazard analysis • Fault tolerance requirements • Failure mode effects analysis inputs ••• CIL inputs • Hardware design, development, testing, evaluation, and production costs • Cost trades	3.6.1 Develop flight guidance and control system strategies 3.6.2 Derive subsystem/component requirements 3.6.3 Determine system performance/margins 3.6.4 Determine induced environments Tools: • General purpose simulations and control system analysis packages such as Matlab and Marshall Systems for Aerospace Simulation (MARSYAS)	• Maximum engine deflection • Control sensor locations • Control surface deflection requirements • Autopilot definition • Guidance system inputs ••• Modified autopilot to reflect a control law for airflow to inlet • Control surface mixing logic • Slosh damping requirements • Q_α versus Q_β envelopes • Flex-body mode frequency constraints • Vehicle transient response to wind disturbances • Pogo suppressor requirements • TVC requirements • Reaction control system (RCS) requirements • Software requirements • Computer requirements • Sensor requirements • Power requirements for control system • Diagnostics/control logic • Technical descriptions • Test requirements to include instrumentation • Product quantities • Make or buy plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 8. Task description, WBS 2.7, Mass properties.

Inputs	Tasks	Outputs
• Program and subsystem definition • Vehicle coordinate system • WBS • Subsystem and hardware basic component mass estimates • Sketches, drawings, parts list, and material identification • Propellant inventory • Flight profile	3.7.1 Develop a mass properties control plan 3.7.2 Set up mass properties database 3.7.3 Input component weight estimates and contingencies into database 3.7.4 Compute center of gravity (CG) and moments of inertia (MOI) 3.7.5 Perform trade studies and mass properties analysis 3.7.6 Calculate mass versus burn time Tools: • Commercial software — CAD packages • In-house software – MP03 MP Accounting System – STS MP Launch Vehicle Program – MP05 MP Launch Vehicle Program	• Mass properties control plan • Mass properties reports: – Current weights – CG's – MOI's – Potential changes – Pending changes – Weight history – Mass versus time • Charts for review • Customized MP information

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 9. Task description, WBS 2.8, Propulsion.

Inputs	Tasks	Outputs
• Projected ground rules, design-to-cost goals • Technology requirements (TRL level) • Engine interface • Redundancy requirements • Programmatic constraints • Launch pad environments • Vehicle configuration and tank geometry • Line routing zones • Pressurant bottle locations ••• Preliminary air column ••• Profile • Vehicle mass versus time • Thrust, acceleration, and pressure versus time • I_{sp} (flow rates) • Usable propellant requirements • Axial acceleration • Dynamic pressures • Flow rates • System dispersions • Wind dispersions ••• Air inlet constraints ••• Derived air volume • Air loads on propulsion elements •• Engine installed thrust ••• Forebody pressure recovery and flow field definition history • Structural analysis of lines and brackets • Establish dynamic envelop of feedline • Determine line thickness ••• Aft/forebody structures • Propellant condition • Temperature time history • Pressure • Chill-down of engine • Temperatures and heating loads • Pogo suppressor requirements • TVC requirements • RCS requirements • Mass properties control plan • Weights, centers of gravity, moments of inertia • Material compatibility • Contamination analysis • Material properties • Thermal and cryogenic properties • Temperature limits • Telemetry capability • Sensor characteristics • Availability of power (current, voltage, phase) • Operational timelines • Maintainability • GSE capability • Vehicle integrated operations concept and requirements • Flight timeline • Fabrication parameters • Flight safety review of schematic and operations • East and west test range interface • Hazard analysis • Fault tolerance requirements • Reliability allocation and estimation • Failure mode effects analysis inputs ••• CIL inputs • Hardware DDT&E and production costs • Cost trades	3.8.1 Establish baseline feed system geometry 3.8.2 Analyze tank/feed system fluid, thermal issues – Temperature profiles – Cryo fluid management – Pressure drop, NPSP availability, water hammer – Residuals ullage – Propellant inventory 3.8.3 Pressurization system sizing and design 3.8.4 Valves, ducts, mechanisms design, and layout drawings 3.8.5 TVC components and design 3.8.6 Propulsion system schematics and layout drawings 3.8.7 Testing engine/propulsion component Tools: • In-house software • Fluid flow models—cryo fluid management thermal models • Testing • Commercial software—CAD layout/drawing packages	• Propellant inventory • Propulsion system layout • Tank pressures • Propellant level sensor locations ••• Forebody moldline (iterate req air volume) ••• Staging requirements ••• Propellant requirements ••• Number of engines ••• Performance updates •• Entry propellant weight • Propellant load • Engine performance (I_{sp}, thrust) ••• Expected engine mach transitions ••• Inlet captive volume ••• Recovery pressures ••• α, for inlet airflow as a function of mach number ••• Mach transitions • Engine dimensional and operational characteristics • Turbine exhaust definition • On-pad effluent definition ••• RBCC exhaust conditions ••• Forebody inlet performance requirements • Ignition and shutdown thrust transients and timing sequences • Steady state thrust oscillation • Ullage pressure and tank fill heights versus flight time ••• RBCC exhaust/thrust • Ground hold conditions • Heat load requirements for propellant conditioning • Chill-down requirements • Engine configuration • Engine operating characteristics • Engine thermal requirements • TVC gimbal capability (degree and rates) • Feedline layout • Kinematic analysis • PU system definition ••• Air capture transition • Propulsion system drawings and models • Component weight estimates • Parts list • Life limits • Instrumentation • Uplink/downlink requirements • Drive electronics • Electrical power requirements • MPS checkout and fill • Refurbishment/inspection requirements • Verification requirements • Transportation requirements • Subsystem definition and design description document • Vehicle controls • Power usage ••• Flight rules • Drawings and schematics • Hazard analysis inputs • Functional failure modes • Failure propagation logic development • Diagnostics/control logic • Failure mode effects analysis inputs ••• CIL inputs • Technical descriptions • Vendor quotes • Test requirements to include instrumentation • Production quantities • Make or buy plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 10. Task description, WBS 2.9, Materials.

Inputs	Tasks	Outputs
• Drawings • Component function • Load/life requirements • Environment – Temperature – Humidity – Pressure • Accessibility • Design engineering and strength requirements • Special material requirements • Material identification and usage list (MIUL) • Assembly operations • Environment restrictions	3.9.1 Compare candidate materials to MIL–HDBK–5 data 3.9.2 Evaluate materials per MSFC–STD–506 and NHB 8060 requirements: Including but not limited to: – Toughness – Compatibility with intended use environments – Life and aging – Corrosion, stress corrosion – Toxicity – Flammability – Reactivity – Flaw environmental and cyclic growth rates 3.9.3 Evaluate fabrication and joining effects 3.9.4 Develop NDE techniques 3.9.5 Conduct static and fatigue tests to obtain missing and needed data 3.9.6 Contamination analysis 3.9.7 Cleanliness evaluation 3.9.8 Critical processes evaluation 3.9.9 Storage and shelf life evaluation 3.9.10 Select materials and processes 3.9.11 Qualification of weld and braze specimens 3.9.12 Develop NDE techniques 3.9.13 Develop contamination and cleanliness control plans	• Fracture mechanics evaluation • Material selection options • Establishment and selection of fabrication techniques • Data for structural analysis • Material usage agreements (MUA) • Materials selection and control plan • Material identification and usage list (MIUL) – final • Process specifications • NDE inspection and implementation procedures • Repair techniques • Hazardous operations evaluation • Process schedules • Personnel certification requirements • NDE plan and data for drawing input • Contamination and cleanliness plans
	Tools: • NASA and MIL databases	

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 11. Task description, WBS 2.10, Communication and data handling.

Inputs	Tasks	Outputs
• Induced environments – Temperatures – Vibration levels – Radiation levels – EMI requirements • Materials allowable • IP&CL • Input power • Weight and volume limits • Range safety requirements • RF coverage requirements • Data rate • Bit error rate • Verification requirements	3.10.1 Flight computer requirements analysis 3.10.2 Input/output including signal conditioning requirements 3.10.3 Software 3.10.4 Ground station coverage analysis 3.10.5 Link margin analysis 3.10.6 Flux density calculations	• Component specs • Software specification • COTS adequacy • RF systems design • Ground station design • Antenna coverage analysis
	Tools: • Commercial software — CAD packages • In-house software — CAE	

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 12. Task description, WBS 2.11, Electrical power system and electrical integration.

Inputs	Tasks	Outputs
• Systems requirements document • Overall project requirements for DDT&E • Preliminary orbital parameters and flight profiles from phase A • Preliminary architecture from phase A • Mission phases and operational scenarios • Thermal environment	3.11.1 Update architecture and specific requirements, orbital parameters and mission phases 3.11.2 Determine component design specifications 3.11.3 Perform electrical power/energy analysis 3.11.4 Develop cable interconnect diagram (CID) and electrical system schematics 3.11.5 Perform parts availability and cost analysis for design options 3.11.6 Determine quality test requirements from program requirements 3.11.7 Identify long lead items and potential technology show stoppers. Prepare alternative for work-arounds 3.11.8 Formulate subsystem test plan and support test and integration activities 3.11.9 Develop subsystem schedule to meet overall program schedule for hardware integration and test 3.11.10 Develop avionics data list for electrical integration task including cable design Tools: • Commercial software — CAD packages • In-house software — CAE	• EPS design and component specification • Battery sizing and specs • Cable interconnect diagram • Electrical system schematics • Cable harness designs • EGSE and support hardware designs • Electrical power distributor design • EPS description and operational limits

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 13. Task description, WBS 2.12, Ground operations.

Inputs	Tasks	Outputs
• Ground test and checkout procedure • Ground operations concept and requirements • GSE design information • Critical interfaces • System and subsystems definition and design description documents • Command and telemetry uplink/downlink data • Subsystem constraints including ground systems • Vehicle and ground systems FMEA • Vehicle coordinate reference frames • Operations sequence diagram • Project ground rules • Environmental constraints • Initial loads data • Safety constraints • Personnel to be trained and description of their flight-operations position	3.12.1 Human factors analysis-task analysis 3.12.2 Define flight and ground operations sequences 3.12.3 Define critical operational decisions 3.12.4 Define specific actions and sequences 3.12.5 Define operations control personnel tasks and responsibilities 3.12.6 Develop flight table parameters 3.12.7 Develop ground command loads 3.12.8 Identify existing facilities available and new facilities requirements 3.12.9 Specify design considerations	• Ground systems and ground operations human factors operability assessment • Launch/flight human factors and operability assessment • Operations sequence diagrams • Decision action diagrams • Launch sequence procedures • Launch team definition • Launch and flight rule development • Integrated operations manual • Launch and flight sequence timelines • Data flow analysis timeline • Facilities required • Facility design and cost plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 14. Task description, WBS 2.13, Flight operations.

Inputs	Tasks	Outputs
• Program guidelines, constraints, ground rules, and program approach • Vehicle and ground system design concepts • Subsystem and end-item design concepts • Operations sequence diagram • Project ground rules • Burn and jettison times • Trajectory constraints • Aerodynamic data • Environmental constraints • Initial loads data • Safety constraints	3.13.1 Develop integrated operations concepts and perform trades and evaluations to arrive the baseline operations approach 3.13.2 Derive the operational requirements from the baseline integrated operations concept and document in the program level system and segment specifications 3.13.3 Perform the functional allocation of the system and segment level operations requirements to the subsystem and end-item levels 3.13.4 Launch and flight sequence scheduling 3.13.5 Data analysis — Data flow assessment	• Baseline integrated operations approach • System and segment level operations requirements • Subsystem and end item operations requirements • Launch and flight sequence timelines • Data flow analysis timeline • Flight load table updates

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 15. Task description, WBS 2.14, Manufacturing processes.

Inputs	Tasks	Outputs
• Drawings • Component function • Assembly operations • Schedules • Inspection and assurance requirements • Cost restrictions • NDE plan • Cleanliness plan • Contamination plan • Quality plan	3.14.1 Develop fabrication and joining techniques 3.14.2 Evaluate fabrication practice: – Forging – Casting – Weldment – Composite – Adhesive – Joining – Etc. 3.14.3 Evaluate material form and selection for best manufacturing practice Tools: • NASA and MIL databases	• Input for drawings, notes, specifications, etc. • Hardware control • Manufacturing control plan • Assembly and verification plan • Make or buy plan input

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 16. Task description, WBS 2.15, Safety processes.

Inputs	Tasks	Outputs
• OSHA and EPA constraints • Severe weather data • Lightning data • Design details • Schematics • Hazard analysis input • Material certifications • Vehicle integrated operations concept and requirements	3.15.1 Review schematics 3.15.2 Review operations concept 3.15.3 Assess test range to assure compliance 3.15.4 Develop hazard analysis document 3.15.5 Develop range safety requirements 3.15.6 Develop safety constraints and guidelines 3.15.7 Conduct vehicle and launch facility FMEA 3.15.8 Quality control plan Tools: • Commercial software—Faultrease, CAFTA, FIRM, FTC • In-house software—FEAS-M, others • Commercial and in-house reliability databases	• Range safety requirements • Hazard analysis • Quality assurance Plan • CIL's • FMEA's • Risk analysis

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 17. Task description, WBS 2.16, Design reliability.

Inputs	Tasks	Outputs
• Design details • Schematics • Structural and functional definition • Environment/loads definition • Structural design analysis • Historical data • Diagnostics/control logic	3.16.1 FMEA/CIL 3.16.2 Failure propagation logic model development – Qualitative analysis – Single-point, dual-point failure – Degradation, fault tolerance – Quantitative – Trade support – Verification of requirements 3.16.3 Time domain analysis 3.16.4 Probabilistic design analysis Tools: • Commercial software—Faultrease, CAFTA, FIRM, FTC, others • In-house Software—FEAS-M, others • Commercial and in-house reliability databases	• System reliability estimates • Component reliability estimates • FMEA/CIL inputs/ requirements • Design reliability model • Test input • Sensitivity and trade support • Integrated risk analysis support • Operations and maintenance model input

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

Table 18. Task description, WBS 2.17, Cost.

Inputs	Tasks	Outputs
• Ground rules and assumptions • WBS • Schedule • Design-to-cost goals • Technology requirements • Reliability • Vehicle technical description • Test requirements • Vehicle weights and quantities • Hardware make/buy plans • Vendor quotes • GSE technical descriptions • Ground/flight test requirements • Operational timelines • Operations crew sizes • Facility/tooling requirements • Software requirements • Business analysis/plan economic parameter inputs	3.17.1 Perform cost trades 3.17.2 Develop WBS 3.17.3 Develop ground rules/assumptions 3.17.4 Develop vehicle DDT&E, facilities, production and operations Cost estimates – Program cost by WBS – Program cost by fiscal year 3.17.5 Develop vehicle cost-per-flight estimates – Develop schedule – Provide procurement support Tools: • Bottoms-up, parametric, and economic models	• Cost trades • WBS • Ground rules/assumptions • Program cost estimate • Commercial vehicle business analysis/plan

Key: • ELV, RLV, and RBCC •• RLV and RBCC ••• RBCC only

3. CONCLUDING REMARKS

A concerted effort has been made to define and document, at a first level, the information flows between the design functions involved in phase C stage of the launch vehicle design process at MSFC. An N×N diagram (table 1) was created to display the flow of data items and the interdisciplinary interfaces. The complexity of the process varies with launch vehicle classification. The complexity of the process increases from ELV to RLV to RBCC. The RBCC class of vehicles adds significant interfaces between the propulsion design function and the other design functions.

The structure of the information flowing between the numerous disciplines forms a complex web. Examination of the N×N diagram reveals that the design and analysis process is complex, the process requires many actions, each action requires certain information before it can be taken, and each action produces information once it has been taken.

The design process must be optimized, and the flow of information must be controlled and tracked to achieve faster, cheaper, and better designs in today's environment of flattened organizations and paperless engineering. The right information must get to the right people at the right time. A number of design planning software tools are available to determine the optimal sequence for process execution once the couplings between the project disciplines have been defined. One such software tool is Design Manager's Aid for Intelligent Decomposition (DeMAID), described in reference 2. It is possible to significantly reduce the time per design cycle. Indeed, an example described in reference 3 shows a reduction in design cycle time from 21,340–4,570 time units.

4. RECOMMENDATIONS

The work to define the information flow between project disciplines should be continued and expanded to:

- Reduce project specific design process models for a recent project and for a current project
- Test available design planning software tools on these project specific models
- Produce optimized design programs (i.e., schedules and plans for the selected projects) and illustrate and incorporate the new design planning methods and tools into this data set.

APPENDIX A—Basic N×N Diagram

N×N diagrams are used to develop data interfaces. The basic N×N diagram is shown in figure 20. Functional blocks that describe the system or process are placed on the diagonal. The functional block describes what the system or process does and not how it is accomplished. The rows and columns of the diagram show the outputs and inputs, which interface the functional blocks. The rows contain outputs from the functional blocks and the columns contain inputs to the functional blocks. Where a blank row-column square exists there is no interface between the corresponding functional blocks. Data flows in a clockwise direction between functions; i.e., the symbol $F_1 \rightarrow F_2$ indicates data flowing from function F_1 to function F_2. Feedback, i.e., data flowing from F_2 to F_1, is indicated by the symbol $F_1 \leftarrow F_2$. The data being transmitted can be defined in the off-diagonal squares. The squares below the diagonal contain data being fed backward (feedback), and the squares above the diagonal contain data being fed forward.

Function 1 F_1	F_1 --> F_2	F_1 --> F_3	F_1 --> F_4
F_1 <-- F_2	Function 2 F_2	F_2 --> F_3	F_2 --> F_4
F_1 <-- F_3	F_2 <-- F_3	Function 3 F_3	F_3 --> F_4
F_1 <-- F_4	F_2 <-- F_4	F_3 <-- F_4	Function 4 F_4

Basic N×N Diagram Rules

- All functions (or subfunctions) are on diagonal.
- All outputs are horizontal (left and right).
- All inputs are vertical (up and down).
- Inputs and outputs are items, not functions.

Figure 20. Basic N×N description.

APPENDIX B—Glossary for the Launch Vehicle N×N Diagram

The terms defined below are found in the N×N diagram (table 1). They are listed in alphabetical order.

Abort alternate mission analyses. Potential abort trajectories footprints.

Active thermal control system sizing. Determine the sizing of the active thermal control system required to thermally protect internal vehicle components such as avionics, etc. This includes selection of the coolant and sizing of the heat rejection system (such as radiators, etc.).

Antennae range data. Line-of-sight vector to vehicle and vehicle attitude.

Ascent trajectory sets. Altitude, mach, angles of attack and sideslip, atmospheric conditions, heating rates, etc.

Ascent wind models. Model to define magnitude and direction of wind versus altitude along the ascent path.

Atmospheric model. Model to define atmospheric parameters (e.g., density, temperature) versus altitude.

Autopilot definition. Controllable flight corridors, maximum rate requirements.

Baseline autopilot configuration. Algorithms and architecture.

Bracket analysis. Structural strength and life assessments of structural brackets utilized in propulsion components.

Burn times. Times at which engines are cutoff or solid motors burn out.

Component installation. Assembly containing component installation.

Component weight estimates. Relates to the weights of active or passive thermal control system components such as pumps, thermal capacitors, etc.

Computer requirements. Required computational cycle frequency for guidance and control execution loops, and transport delay.

Construction type. Honeycomb, isogrid, etc.

Control sensor locations. Body location of rate gyros, accelerometers, GPS antenna, etc.

Control surface deflection requirements. Degrees of deflection required from each aero control surface.

Critical dimensions. Maximum dimensions.

Critical interfaces. Program requirements levied against the design (e.g., no-services tower, hold-down prior to release, etc.).

Cryogenic insulation sizing. Determine cryogenic insulation thickness using PATRAN, TRASYS, and SINDA to achieve required structural temperatures, control boil-off for required propellant quality and loading, prevent air liquefaction, and minimize ice formation.

Design loads. Those loads that the structure is expected to encounter during its life.

Determine line thickness. Establish sufficient dimensions on propulsion lines to assure adequate strength and life.

Dispersion. Failure case trajectories.

Engine placement geometry. Location, cant angle, distance between engines, propellant feed line location, actuator location gimbal envelope, bolt circle, and thermal closeout.

Entry trajectories sets. Altitude, mach, angles of attack and sideslip, atmospheric conditions, heating rates, etc.

Environmental operations constraints. Operational constraints affecting configuration and maintenance of systems (e.g., hydrazine propellant).

EPA and OSHA constraints. Operational constraints affecting configuration and maintenance of systems (e.g., access and venting).

Establish dynamic envelope of feedline. Area around the feedlines which must be maintained clear to account for dynamic deflections during flight.

Factors of safety criteria. Structural strength design and test factors as well as service life factors for space flight hardware development and verification consistent with NASA–STD–5001.

Flex body mode frequency constraints. Frequency stayout regions for vibration modes of the vehicle.

Fracture control requirements. The minimum acceptable requirements to establish an adequate fracture control program for space flight hardware. The design shall be based on these procedures to preclude a catastrophic event when failure of that hardware occurs. The requirements shall be consistent with NASA–STD–5003.

Ground and ascent wind models. Mathematical representations of the wind speed for the various altitudes of flight from ground through ascent and specific launch sites. The representation is determined from measured wind data and statistical methods.

Ground ops. Program requirements to operating from a specified launch platform (e.g., KSC, VAB, airborne launch, etc.).

Ground wind profiles. Existing wind data of specific launch sites is used to determine ground wind loads.

Guidance system inputs. Constraints on conditions at guidance loop initiation (e.g., dynamic pressure, mach number, allowable drift, and performance).

Gust models. Probability level and structure of wind gust (versus altitude).

Hardware design. Hardpoints and lifting points.

Initial performance. Initial estimate of payload performance for given configuration.

I_{sp} (flow rates). Propellant mass flow rates for each engine.

Jettison times. Times at which stage separations occur.

Launch pad environments. Existing data ranging from atmospheric conditions such as sea spray for determining applicable coatings to exhaust deflection systems to determine base loads (from Natural Environment Inputs of 3.1 Vehicle Configuration and Structural Design). Structural temperature predictions due to natural environment analysis conditions (ambient temperatures, solar input, cryogenic loading, and wind velocities) during prelaunch (from Natural Environment Inputs of 3.5 Thermal).

Launch pad geometry. Defines the location and orientation of the vehicle coordinate system when vehicle is on the pad.

Launch platform finite element model. The finite element model of the structure which the launch vehicle sits on and is launched from.

Launch probability requirements. Probability of launch within certain window (due to natural environments).

Life limit. Refers to the loading spectrum associated with hardware life assessments (fatigue, fracture, stress rupture, creep, etc.).

Line routing zones. Line locations and insulation.

Loads. Forces and moments on a structure due to transportation, prelaunch, launch, ascent, and separation/ignition.

Loads analysis on lines. Forces and moments of propellant lines.

Loads and deflections. Cases where deflection, the movement from a reference datum point, is a governing design criterion for the hardware.

Loads trajectory data. Accelerations, dynamic pressure, angles of attack and sideslip.

Margins of safety. Hardware shall be analyzed to show non-negative margins using the required factors of safety. Margin of safety is the fraction by which failure load or stress exceeds the maximum design condition load or stress that has been multiplied by the factor of safety. MOS = (Minimum Material Strength ÷ Maximum Design Condition)–1.0

Maximum Q. Reference maximum dynamic pressure.

Maximum engine deflection. Degrees of required effective TVC throw angle per engine.

Mission definition. Payload mass and required orbit (apogee, perigee, inclination, etc.).

Number of engines. Number of chosen engines for each stage.

Parts list. Required thermal control component.

Performance updates. Latest estimates of payload performance for configuration.

Periodical mass properties report. Weights, centers of gravity, and moments of inertia.

POGO suppressor requirements. Effective compliance required of the accumulator.

Power requirements for control system. Duty cycles and peak power.

Power requirements for thermal control system. Assist electrical group in determining power requirements for thermal control system components such as pumps, heaters, etc.

Pressurant bottle locations. Location, size, and attachments.

Production ops. Program requirements such as using existing tooling from other launch vehicle production lines versus new facilities (e.g., Shuttle-C, ALS/NLS, etc.); also program requirements of quantity (e.g., mass production versus one-of-a-kind).

Production quantities. Quantity needed.

Propellant feedline flex modes. Dynamic mode shapes of propellant feedline structure.

Propellant load versus time. Time history of propellant mass per tank along trajectory.

Propellant requirements. Propellant volume and tank pressure.

Propellant slosh baffle sizing. Geometric dimensions of baffle structure.

Propellant slosh modes. Dynamic mode shapes of propellant fluid surface.

Protuberance geometry. Geometry of objects that protrude from the primary contour.

Q_α versus Q_β envelopes. Maximum product envelopes versus mach number of altitude (including dispersed cases).

QAlpha, QBeta constraints. Maximum and minimum of the dynamic pressure (Q) multiplied by both the angle of attack (Alpha) and sideslip angle (Beta).

RCS requirements. Required thrust, location, and duty cycle for RCS thrusters.

Redundancy requirements. Engine out and thrust vector control failure requirements.

Reference trajectories. Time history, altitude, mach dynamic pressure, vehicle mass, velocity, etc.

Residuals at main engine cutoff, etc. Propellant masses remaining at engine cutoff times.

Sensor requirements. Required number, type, sensitivity, bandwidth, accuracy, etc. of sensors.

Shock sources. Springs, latches, separation devices, recovery devices (e.g., parachutes).

Slosh damping requirements. Percentage damping required for each propellant tank versus time of fluid height.

Software requirements. Algorithms required to implement guidance and control system functions.

Stability margins. Achievable gain and phase margins for autopilot system.

Staging requirements. Number of stages and staging conditions (e.g., location, altitude, and velocity).

Structural design analysis. Ensure that the structure has the capability to successfully withstand the specified loads for the required life.

Structural dynamic models and analyses. Finite element models used for analysis that is concurrent with motion; i.e., dynamic analysis.

Structural failure modes. Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments, or to function as designed.

Structural sizing. Critical dimensions of structural members needed to meet the strength, stiffness, stability, and life requirements.

Structural temperature requirements. Materials group provides thermophysical properties schemes, density, specific heat, thermal conductivity, and melt temperature. Thermal test program required to verify thermal protection material adequacy for application on vehicle is established by thermal and material groups. Thermal group assess material ablation rate as function of heating from test.

Structural temperatures and gradients. Structural margin evaluation determines allowable temperatures for specific location on vehicle. Thermal group determines required thermal protection system to maintain acceptable structural temperatures.

Subsystem definition. Program-defined components (e.g., existing engine versus paper engine, proven technology versus cutting edge, solids versus no solids, etc.).

Subsystem definition and design description document. Extreme temperature ranges are –40° F to 165° F (aircraft flying at altitudes above 18,000 ft may be exposed to temperatures below –40° F, therefore, care shall be taken when shipping by air to ensure that the component is properly insulated and shipped in a conditioned compartment that does not exceed the design specification temperature limits.

System dispersions. Thrust, I_{sp}, mixture ratio, GLOW, performance sensitivities due to these.

Technical descriptions. Material type, construction, and size.

Temperature sensor locations. Determine the placement of temperature sensors to evaluate system performance and for comparison with preflight predictions.

Test requirements and support. Strength, modal survey, acoustic, random vibration, and shock.

Test requirements to include instrumentation. Develop test requirements necessary to verify strength of the design (qualification, acceptance, or proof), test to verify strength models, and tests to verify workmanship and material quality of flight articles (acceptance or proof).

Thermal environment. Perform thermal analysis to determine the thermal environments and temperature response of electrical components during prelaunch (cold/hot) ascent, mission operation, and reentry.

Thermal environment for EPS. Electrical group furnishes cable description and allowable temperatures to thermal group. Electronic component group furnishes black box drawings, heat dissipation, and allowable operating and nonoperating temperatures. Temperature ranges for black box qualification are furnished by thermal to electrical group. Thermal group determines the effective operational temperatures of electrical components during prelaunch and flight (ascent, reentry, and landing).

Thermal protections system sizing. Thermal group uses such analytical tools as ABL, PATRAN, TRASYS, SINDA and ACE/CMA along with prelaunch environmental conditions and flight heating environments to select TPS material type and thickness/weight based on maximum temperature and heat load. These data are supplied to assist designers in material selection and vehicle design.

Thermal protections system sizing (aerothermal/base heating). Use of analytical tools such as ABL, PATRAN, TRASYS, SINDA, and ACE/CMA to provide required TPS/insulation weight.

Time history. Vehicle attitude, throttle settings, burn times, jettison times, GLOW.

Transportation loads. Forces and moments of structure due to transportation.

Transportation requirements. Requirements for transporting hardware (e.g., maintaining a positive pressure, enclosed shipping container).

TVC requirements. Required gimbal angles, rates, acceleration, duty cycles for TVC actuators, throttle range, and rate requirements.

Use and operational environments. Issues such as recovery to determine required systems.

Vehicle breakup and disposal analysis. Reentry footprint and boost stage impact footprint.

Vehicle configuration and tank geometry. Two-dimensional layouts and three-dimensional models containing vehicle dimensions, line routing zones, and pressurant bottle locations.

Vehicle coordinate system. X, Y, Z axes for the vehicle (at input to 3.13 Flight Operations). Location of origin, orientation of axes, and units (at External Input for 3.7 Mass Properties).

Vehicle flex-body modes. Structural dynamic characteristics of a vehicle.

Vehicle moldline. External contour of the vehicle.

Verification requirements. Verify that no design parameters were exceeded during shipping (e.g., manufactured part equals shipped part).

Vibro-acoustical requirements. Vibration criteria used to qualify electronic hardware for launch vehicle environments.

Wind dispersions. Performance penalty due to winds.

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13. ABSTRACT *(Maximum 200 words)*
This paper describes the results of a team effort aimed at defining the information flow between disciplines at the Marshall Space Flight Center (MSFC) engaged in the design of space launch vehicles. The information flow is modeled at a first level and is described using three types of templates: an N×N diagram, discipline flow diagrams, and discipline task descriptions. It is intended to provide engineers with an understanding of the connections between what they do and where it fits in the overall design process of the project. It is also intended to provide design managers with a better understanding of information flow in the launch vehicle design cycle.

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