Leveraging History in the Context of Project Engineer Education: *Project Mercury*

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Abstract

The first manned U.S. space program, *Project Mercury*, is leveraged as a data-rich aerospace systems engineering design case study. The extensive amount of contract design reports, technical memorandums, and project overviews documented by NASA and the prime contractor, McDonnell Aircraft Corporation, allow for a comprehensive data-base (DB) and knowledge-base (KB) buildup. Emphasis is placed on identifying, retaining and integrating available *Project Mercury* knowledge to the aerospace community into a physics-based parametric sizing (PS) process. The primary goal is to reverse-engineer the principal *Project Mercury* vehicles, as well as to reverse-engineer top-level design and program architecture decisions leading to the successful system design.

In order to provide a consistent, objective assessment, the total vehicle system performance is quantified with an existing, validated PS process and is gauged numerically based on technical, operational, and political requirements set forth by the US government and NASA. The process of reverse engineering the design decisions made in the history-making *Project Mercury* lays the framework for modern engineers to leverage past knowledge to better understand the potential solutions of today's aerospace challenges.

Introduction

The modern engineer is in a very unique position. There is an enormous amount of knowledge available from past engineering efforts readily available. One hundred plus years of aerospace knowledge build-up and millions of engineers' careers can be found in books, internal company documents, technical memorandums, design reports, press briefings and others. The concern for the modern engineer is the overabundance of information, and the lack of time and emphasis by most engineering environments to utilize historic documents, thus lessons learned. It is the intention of the Aerospace Vehicle Design (AVD) Laboratory at the University of Texas at Arlington to demonstrate with an example best-practice design re-engineering case study, how today's engineers can leverage a historic project like *Project Mercury* to gain insight and increase systems-level design proficiency.

Project Mercury Introduction

Project Mercury was a minimum complexity space system intended to put one man in space orbit for a limited amount of time. The system comprised of a (1) rocket launcher, and (2) re-entry capsule, both of which heavily leveraged on existing technical and industrial capability available at the time of design. Mercury was in direct competition at the time of actual engineering to the Soviet Vostok system, which is assessed here in parallel as a reference and for competition analysis purposes.

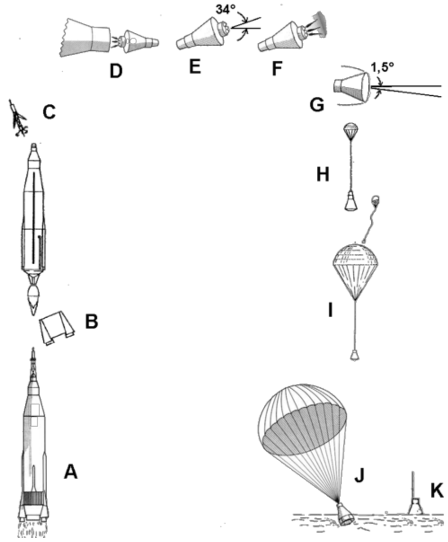


Figure 1. Reference Mission for Project Mercury [1]

The following is a direct excerpt from the *Congressional Panel for Manned Space Flight* in October of 1958, directly before the official start of *Project Mercury*. Sections have been selected here that effectively locked the mission and the overall configuration design.

I. OBJECTIVES

> The objectives of the project are to achieve at the earliest practicable date orbital flight and successful recovery of a manned satellite, and to investigate the capabilities of man in this environment.
>
> II. MISSION
>
> To accomplish these objectives, the most reliable available boost system will be used. A nearly circular orbit will be established at an altitude sufficiently high to permit a 24-hour satellite lifetime; however, the number of orbital cycles is arbitrary. Descent from orbit will be initiated by the application of retro-thrust. Parachutes will be deployed after the vehicle has been slowed down by aerodynamic drag, and recovery on land or water will be possible.
>
> III. CONFIGURATION
>
> A. Vehicle
>
> The vehicle will be a ballistic capsule with high aerodynamic drag. It should be statically stable over the Mach number range corresponding to flight within the atmosphere. Structurally, the capsule will be designed to withstand any combination of acceleration, heat loads, and aerodynamic forces that might occur during boost and reentry of successful or aborted missions.
>
> …
>
> D. Retrograde System
>
> The retro-rocket system will supply sufficient impulse to permit atmospheric entry in less than 1⁄2 revolution after application of retro-thrust. The magnitude and direction of the retro-thrust will be predetermined on the basis of allowable declarations and heating within the atmosphere, and miss distance.
>
> …

Research Project Introduction

The goals of the present research project are to (a) utilize *Project Mercury* as a case study to integrate the DB-KB-PP forecasting modules, (b) calibrate the AVD Laboratory parametric sizing process for a total space architecture, (c) gain experience with a multi-disciplinary design team, and (d) retrieve systems engineering knowledge from a highly successful national space program. The semester-long research project has the ultimate goal of reverse engineering the primary Mercury flight vehicle system by adopting the identical design-constraining mission, requirements, limitations, and vehicle elements.

Research Project Structure

In order to correctly implement any engineering forecasting activity, it has been established that an industry best-practice approach requires a Data-Base (DB), Knowledge-Base (KB), and Parametric Process (PP). Figure 2 illustrates the logic flow of information between the three tools; the primary tasks of each module are indicated in order to successfully support forecasting the total system performance.

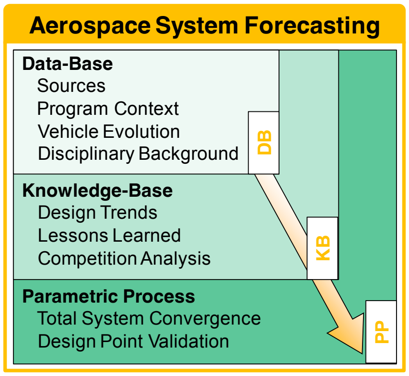


Figure 2. Design Process Hierarchy

Data-Base (DB)

A Data-Base is defined as a collection of data or information organized for rapid search and retrieval, especially by a computer. While the use of a DB is not groundbreaking in many fields, the development of a structured DB covering varied levels of information in support of an engineering design effort is seen as a novel contribution. A condensed literature survey is performed at the beginning of research project and each member is assigned a minimum amount of general project documents to associate each source with the data it contains (topic, scope, depth). Research team members are encouraged to continue a systematic update of any new references or indexes within current references they encounter in their individual research tasks throughout their research period. In this manner, the DB is a dynamic tool that will be leveraged in all further research efforts.

Knowledge-Base (KB)

A Knowledge-Base is a somewhat more loosely defined term. In practice, a KB is a collection of condensed information from a previous research that provides some level of insight into a specific field. This knowledge can either come from data included in the DB or from separate research that has commonality with the current project. Discipline-specific technical methods, rules of thumb, and design trends are examples of information found in the KB.

Parametric-Process (PP)

A Parametric Process is a multidisciplinary model that logically connects numerical methods describing all relevant technical aspects of the elements needed to describe the total system in question. Given a set of system performance requirements and an initial guess for its characteristics, a PP must stably converge through numerical iteration. Final output is the size, weight, and performance of a vehicle system that satisfies the given information considering the mission requirements. A framework parametric process is in place from previous work at the AVD Laboratory and is leveraged for sizing activities.

Research Team Structure

The research team for the re-engineering task of *Project Mercury* is segmented into four teams; the first three roughly representing the flight segments (Ascent, Reentry, Landing), whilst the fourth team engages in a concurrent effort using the Space Planner design text. The Chief Engineer is responsible for integrating the analytical work of all teams into the sizing synthesis environment.

Ascent Team

The ascent team is mainly focused on the rocket booster required to send a manned capsule into a low earth orbit (LEO). The actual development cycle saw use of two smaller, single-stage rockets for testing and suborbital flight tests (Little Joe and Redstone) and a production, two-stage launcher for orbital flights (Atlas). The ascent team characterizes the performance and development of these three launch vehicles.

Reentry Team

The reentry team is tasked with characterizing the Mercury capsule. This includes mission requirements, technology development/utilization, and vehicle performance. The development process of the Mercury capsule is also detailed to understand how the testing environment surrounding the design process shaped the final capsule product.

Landing Team

The landing team deals with the final segment of the capsule return to earth. The parachute and landing system performance is determined after the capsule's size and weight is fully determined. Therefore, this demanding flight segment for the capsule requires its own research team.

Space Planners Guide Team

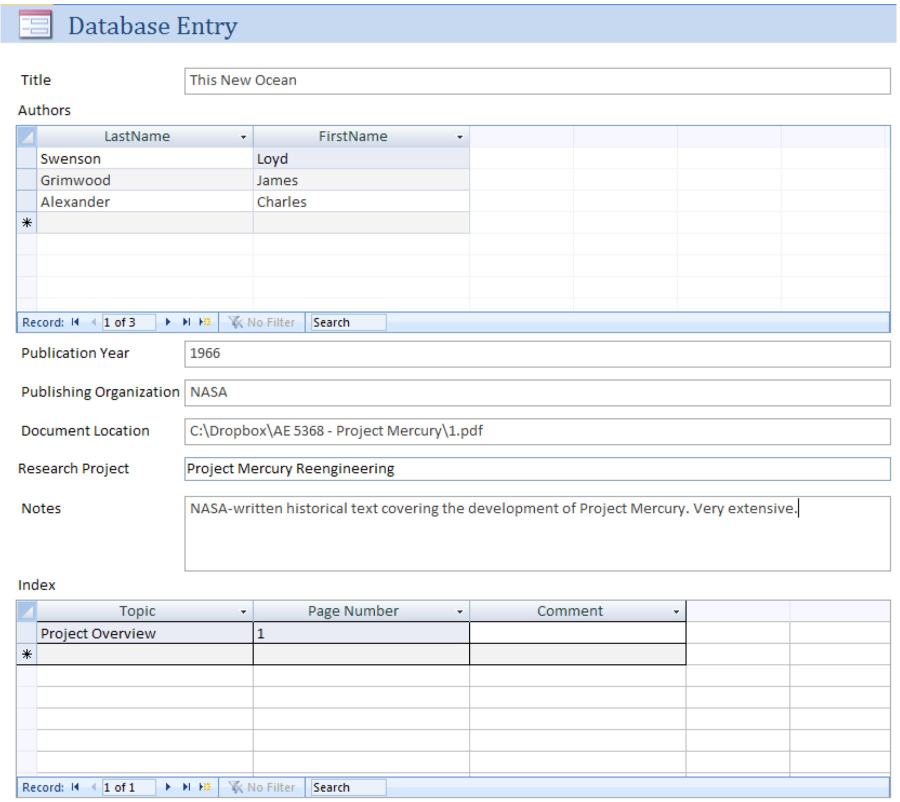
This activity seeks to understand and utilize the *USAF Space Planners Guide* [2] document which allows an engineer to perform a focused, empirically-based synthesis of a space vehicle system. The *USAF Space Planners Guide* regressions include *Project Mercury* and will therefore provide a trustworthy sanity check of the design results otherwise generated.

Data-Base and Knowledge-Base

To initiate the research project, the design team undertakes an effort to harvest knowledge from historic documents (source database) and convert that information into a useable format for use in the parametric sizing process (vehicle main data-sheet). The source database is an organized collection of all reference materials used during the re-engineering study. Standard bibliography information is logged and specific sections of documents where useful information can be found are indexed for further use. The main data-sheet (MDS) is a collection of all pertinent engineering information about a vehicle. All values presented in the MDS are cross-linked with the reference that supports it to provide full transparency.

Source Database

Because of the amount of data available about *Project Mercury*, it is desired to have a systematic and organized method for storing and extracting information. Implementation of the DB is a searchable Microsoft Access database that allows users from different backgrounds, focuses, and research levels to contribute data in a consistent manner. All available sources have a generic bibliography, followed by a more detailed catalog of the discipline-specific information contained. It is the goal of the indexing process to re-create the feeling of going through a physical text and labeling sticky notes on the most important sections.



Title: This New Ocean

Authors

LastName	FirstName
Swenson	Loyd
Grimwood	James
Alexander	Charles

Publication Year: 1966

Publishing Organization: NASA

Document Location: C:\Dropbox\AE 5368 - Project Mercury\1.pdf

Research Project: Project Mercury Reengineering

Notes: NASA-written historical text covering the development of Project Mercury. Very extensive.

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Figure 3. Access Source Information Form

Main Data Sheet

The vehicle main data sheet (MDS) mirrors a traditional aerospace vehicle data-base aimed at keeping track of technical values for a vehicle. The current system allows for different categories of vehicles to have their own set of pertinent variables, but at the same time reside within the same generic database. For this research project, *hypersonic vehicles* and *launch vehicles* are separated due to their inherent differences and the need for different technical values based on the type of vehicle.

Hypersonic Vehicle MDS

The hypersonic vehicle datasheet contains all information needed to describe the Mercury and Vostok capsules. The data fields describe a generic hypersonic vehicle; therefore, some fields are not relevant. Data is decomposed into general project-level information and more detailed discipline-specific data that is for the parametric sizing process.

Launch Vehicle MDS

The launch vehicle datasheet contains information about the launch vehicle pertinent to the *Project Mercury* re-engineering effort. Because Mercury was tested in an incremental fashion, data about the Redstone, Atlas (and its variants), alternative US launch systems available at the time, and the Soviet Vostok rocket are all included. The field categories are based on the *International Reference Guide to Space Launch Systems* [3] and the parameters needed for later parametric sizing methods.

Knowledge-Base

The current KB consists of a prototype disciplinary methods library. Because the KB is implemented within the same data-base file as the *Source Database* and *Main Data Sheets*, references describing the method are linked to the DB, and method-specific variables are logged for PP sizing. Continuity between the DB-KB-PP environments is seen as key to producing a novel case-study effort.

Parametric Sizing

Previous AVD research is leveraged to perform parametric sizing for the Mercury re-engineering task. A modular, multi-disciplinary analysis methodology is put in place to determine the size, weight, and performance of a vehicle system for a known mission. In summary, the computer program takes in the mission, technologies assumed, and performance required as input and calculates a converged vehicle design or vehicle design trade space. The sizing code ($\text{AVD}^{\text{SIZING}}$) has previously been used, validated, and verified for vehicles with broad missions, technology assumptions, and vehicle concepts. The basis for hypersonic vehicle sizing is taken from previous work initiated by Coleman [4] based on the text by Czysz [5].

Programming Structure

The most current version of $\text{AVD}^{\text{SIZING}}$ is implemented using the MATLAB/Octave programming code. Each disciplinary method is found within its own function file to ensure modularity. Methods within one discipline may change based on driving parameters (i.e. aerodynamic methods change with Mach number). The connection between different disciplines is handled within a separate convergence function which can be adapted for novel architectures. All information that is vehicle specific and held constant throughout the design simulation is held within a unique vehicle input file.

Methods

At the heart of the sizing process are the disciplinary methods that are responsible for analysis. At the beginning of an iteration, the vehicle size and/or weight is estimated for use as a starting point. The analysis methods, see Table 1, are compiled in a systematic progression to produce an updated estimate for the vehicle size, weight, and performance that is the starting point for the successive iteration.

Table 1. Parametric Sizing Disciplines

Discipline	**Input**	**Output**
Convergence	Input file	Converged vehicle
Geometry	Vehicle size	Geometric description
Aerodynamics	Flight condition, geometry	Aerodynamic coefficients
Propulsion	Flight condition	Propulsion performance
Trajectory	Geometry, weight, aerodynamics, propulsion	Trajectory profile
Heating	Trajectory, geometry	Heating environment
Weight & Volume	Geometry, propulsion, trajectory, heating	Weight & volume breakdown

Convergence

Convergence, in the context of AVD$^{\text{SIZING}}$, is the practice of iterating a design-driving variable until the vehicle size and weight are held within error bounds for two successive iterations. The number and type of variables used for convergence is dependent on the complexity of the vehicle system. The process of convergence is constant for all vehicle elements, but the steps, analysis, and convergence criteria may change.

Capsule

The capsule is converged using the planform area and the wing loading (gross weight divided by planform area) as the input variables, with wing loading and capsule weight being the converging variables. The wing loading convergence requires the vehicle to be at a stable convergence, and the capsule weight convergence requires a feasible design under the analysis methods assumed. At the end of each convergence cycle, the current value for capsule gross weight updates the stored wing loading value. The difference between the old and new values must be driven to zero. The capsule operating weight empty (OWE) is determined in two different methods: (1) using the capsule volume from Geometry, and (2) using a systems buildup methodology.

Table 2. Capsule Convergence Criteria

Convergence Variable	**Converging Variable**
Planform Area	OWE from Weight Buildup – OWE from Volume Buildup
Wing Loading	Wing Loading (Previous Iteration) – Wing Loading (Current)

Launch Vehicle

Launch vehicles are sized with a known payload (capsule + retro-rocket + escape tower + adapter) and total stack height. The convergence variable used is the ratio of takeoff gross weight to total stack height of the launch vehicle (stack loading). The vehicle is simulated until the capsule is run through trajectory and the maximum altitude is reached. The total stack height is input as a design variable to identify the solution space for alternative launch options given a known capsule payload.

Table 3. Launch Vehicle Convergence Criteria

Convergence Variable	**Converging Variable**
Stack Loading	Stack Loading (Previous Iteration) – Stack Loading (Current)

Geometry

Capsule

The Mercury capsule geometry is described as a spherically-capped conical frustrum with a small cylinder extending from the top. This basic geometric shape is assumed to remain constant for all vehicle designs considered. The top adapter diameter is a fixed dimension; the ratio of total capsule diameter to nose radius is constant; the geometry of the capsule can be described by knowing only the planform area (an input variable).

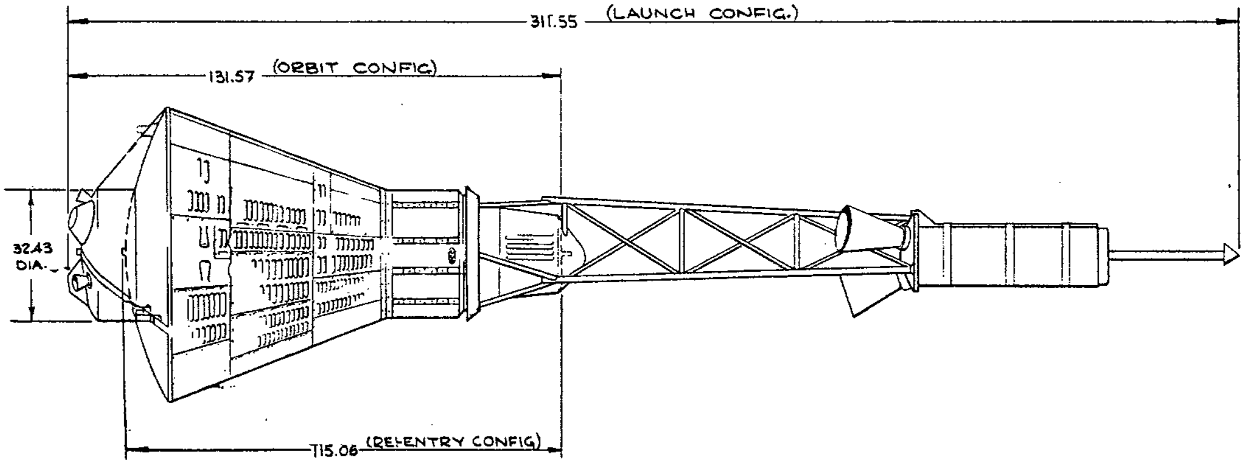


Figure 4. Mercury Capsule [6]

The Vostok capsule (descent module in Figure 5. Vostok Capsule) sheds its asymmetric service module after the retro-rocket is fired, becoming a sphere during the reentry portion of the mission. Like Mercury, the planform area is sufficient to describe the Vostok geometry.

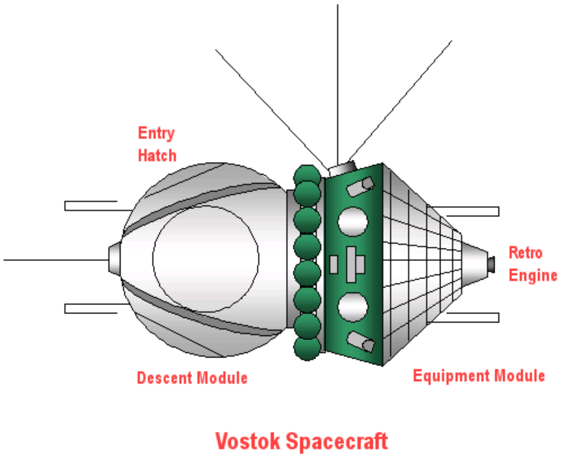


Figure 5. Vostok Capsule [7]

Launch Vehicles

All launch vehicles are considered to be fixed-diameter cylinders for sizing purposes. The maximum diameter is determined by the launch facilities available to the specific vehicle, and the height is solved for as a convergence variable.

Aerodynamics

Capsule

Both the Mercury and Vostok capsule configurations were studied in great detail during the design phase of *Project Mercury*; therefore extensive wind tunnel data is available throughout the relevant Mach number range. In order to reduce the complexity and run time of the sizing program, the aerodynamics are implemented as an empirical method directly from the experimental results. Using actual vehicle aerodynamic data reduces the generic quality of the method, but this approach is simple to implement and allows for modularity between vehicles with similarly explored aerodynamic characteristics.

Launch Vehicles

Like the capsule, launch vehicle aerodynamics are described empirically. Mercury-Redstone reported values are used to create a lookup function for drag coefficient as a function of Mach.

Propulsion

Capsule

The in-orbit ΔV's for insertion and de-orbit are modeled as instantaneous changes in velocity that are accompanied by losses in mass (fuel burn and/or propulsion element jettison). Because of this assumption, a propulsion disciplinary method is not needed for the capsules, only technology-related values for retro-rocket performance in the input file.

Launch Vehicle

Disciplinary analysis for launch vehicle propulsion uses an estimation method for liquid rocket performance (Pratt & Whitney Method). The user input for this method includes the thrust and specific impulse of the rocket in vacuum, as well as the rocket chamber pressure, and nozzle area ratio. Output is the thrust and specific impulse as a function of altitude. It is assumed that alternative launch vehicle concepts considered for *Project Mercury* would have made use of available rocket engines and would not have developed an engine from scratch.

Trajectory

The trajectory for the entire flight envelope is reduced to a 2-D, time-integrated series of equations. Because of the mission profile (no change of orbital plane) and the ballistic re-entry (no lift), the assumption is made that the trajectory can be adequately described by the altitude, range, velocity, flight path angle, and time. Integration is carried out numerically with a Runge-Kutta differential equation solution technique. The integration requires drag coefficient from aerodynamics, thrust from propulsion, weight from weight & volume, an atmospheric model, and a gravity model.

Capsule

The capsule trajectory is initialized from a design orbit and a specified retro-burn. This inserts the capsule into a re-entry trajectory. Both Mercury and Vostok missions have ballistic re-entry trajectories with a fixed zero degrees angle of attack. For sizing purposes, only the re-entry portion through the upper atmosphere is critical. Parachute deployment and landing is modeled as step changes in aerodynamic methods (calculation of drag coefficient), but is done only for completeness and parachute sizing. The landing flight phase does not produce any design-driving parameters for the capsule.

Launch Vehicle

During each convergence iteration, the payload weight of the launcher (capsule + retro-engines + escape tower + adapter) is considered a fixed value. The launcher accelerates upwards until all the fuel is expended, the payload is separated from the launcher, and the payload is integrated within trajectory until reaching a maximum altitude. In the case of the Redstone mission, the capsule is further integrated until parachute opening altitude because of the driving mission constraints (weightlessness time and maximum re-entry acceleration).

Heating

Heating analysis is only performed for the capsule during the reentry phase of the mission. All other combinations of vehicle elements and mission phase are non-critical. Values for the heating rate are obtained by utilizing a semi-empirical engineering relation for stagnation-point heat transfer rate on a sphere developed by Fay and Riddell [8]. The inputs required are the geometry (nose radius) and the trajectory (velocity, density). Both the Mercury and Vostok capsules have spherical heat shields, therefore the method is directly applicable with the definition of the nose radius solved for in the respective geometry modules.

Weight and Volume

Capsule

Capsule weight is determined by using a weight and volume budget methodology from Hypersonic Convergence [5]. The methodology is generic in its formulation, but because the re-entry capsule does not requires weight and volume allocations for propulsion elements, the following variables are the driving weights/volumes, see Table 4. Capsule Weight Method Variables of Merit

Table 4. Capsule Weight Method Variables of Merit

Variable	Description
WSTR	Structure Weight
WOPER	Operational Weight
WSYS	Systems Weight
WMARGIN	Empty Weight Margin
OEW_W	Empty Weight from Weight Budget
V_SYS	Systems Volume
V_PAY	Payload Volume
V_CREW	Crew Volume
V_VOID	Void Volume
OEW_V	Empty Weight from Volume Budget

Each component of weight and volume is calculated using a combination of non-dimensional correlation factors and fixed values (i.e. *Void Volume* is specified in the input file as a fixed percentage of total vehicle volume, *Crew Volume* is input as a fixed, dimensioned design variable). This allows the weights and volumes to be divided between subsystems that are independent of the vehicle size and those that are dependent of the vehicle size.

Launch Vehicle

The disciplinary weight method for launch vehicles uses a component buildup process. Empirical relations for each component are implemented and calibrated separately to match the line by line and total weight values of the launch vehicle.

Table 5. Launch Vehicle Weight Method Variables of Merit

Variable	**Description**
WB	Body Weight
WVF	Vertical Fin Weight
WENG	Engine Weight
WTNK	Tank Weight
WADPTR	Adapter Weight
WSYS	Systems Weight
WBLLST	Ballast Weight
TOGW	Takeoff Gross Weight

Results

Space Planners Guide

The Space Planners Guide [2] was created by the United States Air Force in 1965 to provide a *"... first approximation for evaluating conceptual space missions ..."* and to *"... reduce complex analyses to a straightforward step-by-step procedure. ..."* It uses a series of inter-related empirical curves (nomographs) to give a first order estimate of the size, weight, and performance of space system elements. Figure 6 shows an example how one of the nomographs is used in practice. This specific graph gives an initial estimate of re-entry weight for a manned capsule which is then used as an input to more detailed systems-level weight estimation.

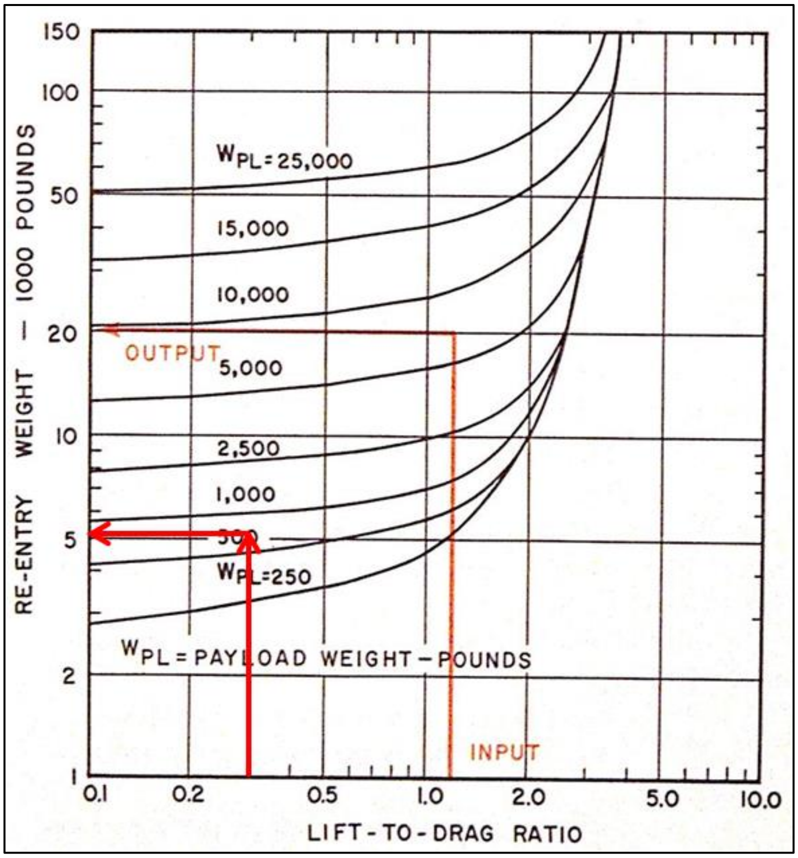


Figure 6. Nomograph to Determine Initial Reentry Weight Estimate [2]

The Space Planners Guide (SPG) is capable of performing systems definition for both re-entry vehicles and for launch vehicles. Therefore, Mercury, Atlas, and Redstone have all been assessed with the SPG. The results in Table 6 show an acceptable error bound in determining the size, weight, and performance of all vehicles except for Atlas, which can be attributed to the non-standard staging of the Atlas first stage boosters. Overall, the SPG provides a very sufficient early design analysis if considering a vehicle and mission within its intended range of applicability.

Table 6. Space Planners Guide Results & Comparison

		SPG	Actual	Units	%Error
Mercury Capsule	Orbital Weight	1,207.0	1,237.2	kg	2%
	Takeoff Weight	1,978.1	1,938.7	kg	2%
Atlas Launch Vehicle	Orbital Velocity	7,650.5	7,858.0	m/s	3%
	Gross Weight	155850.7	116,074.3	kg	34%
	Height	27.4	25.0	m	10%
	Diameter	3.7	3.0	m	20%
	Thrust	1,986,887.1	1,587,192.2	N	25%
Redstone Launch Vehicle	Maximum Velocity	2,295.1	2,324.4	m/s	1%
	Gross Weight	27,693.6	28,394.9	kg	2%
	Height	18.3	19.8	m	8%
	Diameter	1.5	1.8	m	14%
	Thrust	353,055.3	356,996.5	N	1%

Parametric Sizing Design Point Validation

In order to continue with any design trade studies, the parametric sizing process must be calibrated. A design reference mission is used as the input, and method-specific variables are calculated or iterated until the simulated vehicle matches the actual vehicle. The result is an individual point design (the vehicle is not put in context of other solution possibilities). Because the overall goal of the reverse engineering case-study is correctness not accuracy, any error within 10% is considered tolerable. Correct sensitivity to input variables is the key to insightful design trade conclusions, and is verified as well.

Mercury Capsule

The capsule sizing has been decoupled from trajectory and heating due to time and complexity limitations. Because of the narrow design envelope considered for this research, the geometry and weight is considered only a function of their own disciplinary design inputs, while the mission only has an effect on the performance (i.e. a capsule will be roughly the same size and require the same technology for a 100 km orbital mission as a 150 km orbital mission, but the reentry performance will vary between the two missions).

The Mercury-Atlas 7 mission is used as the input for the Mercury capsule design point, because the orbital Atlas missions are much closer to the design-limiting cases than the Mercury-

Redstone demonstration missions. The Redstone missions were tests of operational capability and logistics and do not push the design towards the design-constraining flight conditions that define the capsule requirements. The top-level geometry, weights, and volume results for a MA-7 mission-sized capsule are shown in Table 7 and the design point geometry is shown overlaid with the actual Mercury mold line in Figure 7.

Table 7. Parametric Sizing Design Point Capsule Results & Comparison

	Sizing	**Actual**	**Units**	**%Error**
Orbital Weight	1,241.6	1,237.2	kg	0.4%
Structure Weight	422.2	409.8	kg	3.0%
Systems Weight	432.5	445.0	kg	2.8%
Propulsion Weight	225.0	222.0	kg	1.4%
Total Volume	3.4	3.2	m^3	6.2%
Systems Volume	0.9	1.0	m^3	10.0%
Planform Area	3.1	2.8	m^2	10.7%
Wetted Area	14.2	13.8	m^2	2.9%
Capsule Diameter	2.0	1.9	m	5.3%

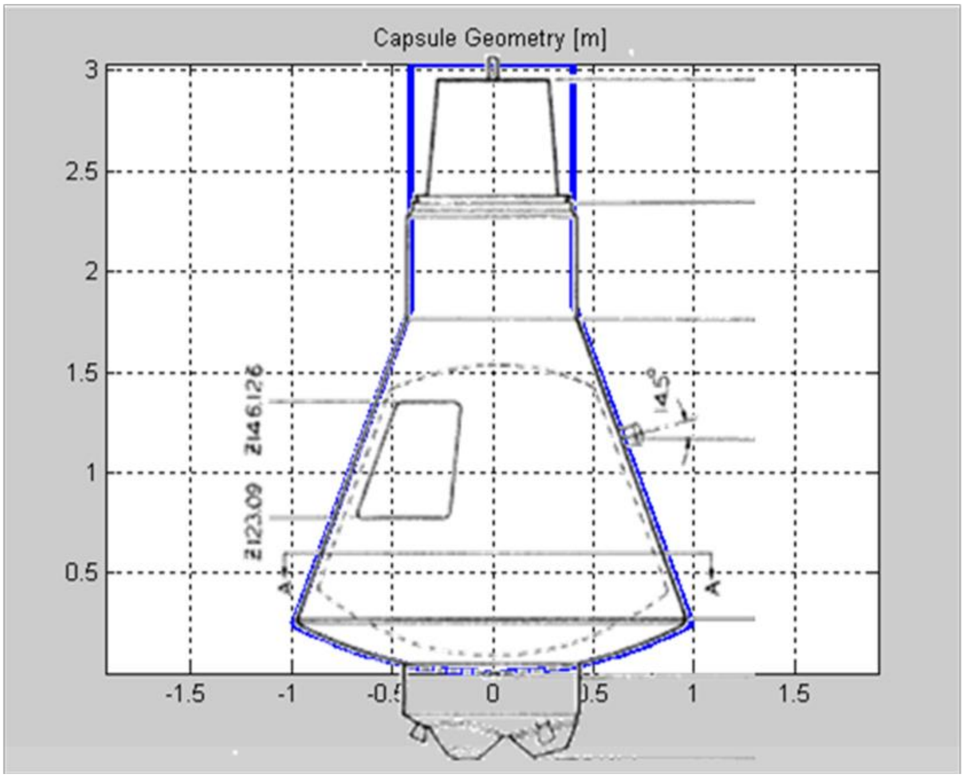


Figure 7. Design Point Capsule Geometry [6]

Redstone Launch Vehicle

The Mercury-Redstone 3 mission is chosen to calibrate the launch vehicle sizing process because of its simple single-stage configuration, and straight-forward performance objectives. Table 8 shows the results of the sizing results and illustrates a very correct and accurate design point.

Table 8. Parametric Design Point Launch Vehicle Results & Comparison

	Parametric Sizing	**Mercury Redstone**	**Units**	**% Error**
Booster Height	17.3	17.5	m	-0.8%
Booster Diameter	1.8	1.8	m	0.0%
Wetted Area	96.9	97.7	m^2	-0.8%
Tank Volume	26.8	27.0	m^3	-0.5%
Tank Height	10.8	10.9	m	-0.6%
Fuel Fraction	0.8	0.8		-0.1%
Operating Empty Weight	3,868.1	3,875.5	kg	-0.2%
Operating Weight Empty	5,523.4	5,530.7	kg	-0.1%
Fuel Weight	24,310.7	24,436.4	kg	-0.5%
Takeoff Gross Weight	29,834.1	29,967.0	kg	-0.4%

Design Trades

With a calibrated, converging model for a LEO capsule – expendable booster space architecture, design-driving input variables can be identified and then varied to create a design trade space that consists of converged vehicles offering alternative design choices. The goal is to identify the interrelationship between design variables and the overall vehicle size, weight, and performance. Physical and technological constraints are added to the design space to illustrate which grouping of vehicle options are feasible and which vehicle options violate the Mercury program constraints, and are therefore unfeasible designs for the given mission and technology.

Constraints

Size, weight, and performance requirements are pulled from various sources that must be considered in the early design phase. For ease of implementation, all constraints have been added passively in post-processing. This means a vehicle can be a plausible, converged design but because it violates a constraint, it is not feasible for the given combination of technology and mission. In this way, the engineer can see the entire range of vehicle possibilities and at the same time see the smaller range of acceptable possibilities.

Capsule

Table 9. Capsule Constraints

Constraint Variable	Value	Reason
Longitudinal Acceleration	11 g	Maximum tolerable amount for astronaut
Maximum Heating Rate	300 W/cm^2	Approximate max. for ablative TPS of era
Capsule Diameter	1.78 m	Atlas max. payload diameter
	2.56 m	Vostok max. payload diameter
Orbital Weight	1,400 kg	Atlas max. orbital mass [LEO]
	4,400 kg	Vostok max. orbital mass [LEO]

Launch Vehicle

Table 10. Launch Vehicle Constraints

Constraint Variable	Value	Reason
Longitudinal Acceleration	11 g	Maximum tolerable amount for astronaut
Weightless Time (Redstone Mission)	5 min	Operational goal for test mission

Capsule Trades

Volume per Crew Trade

In order to justify the designer's choice for the overall size of the Mercury capsule, a design-driving input needs to be varied while keeping the design mission constant. The volume allotted for the crew member is chosen as the key variable to keep volumetric efficiency (and as a product the aerodynamic performance) roughly constant, while allowing the capsule to grow or contract based on the input, see Figure 8. In this way a family of possible Mercury capsules can be identified that fit within the launch capabilities and re-entry performance requirements.

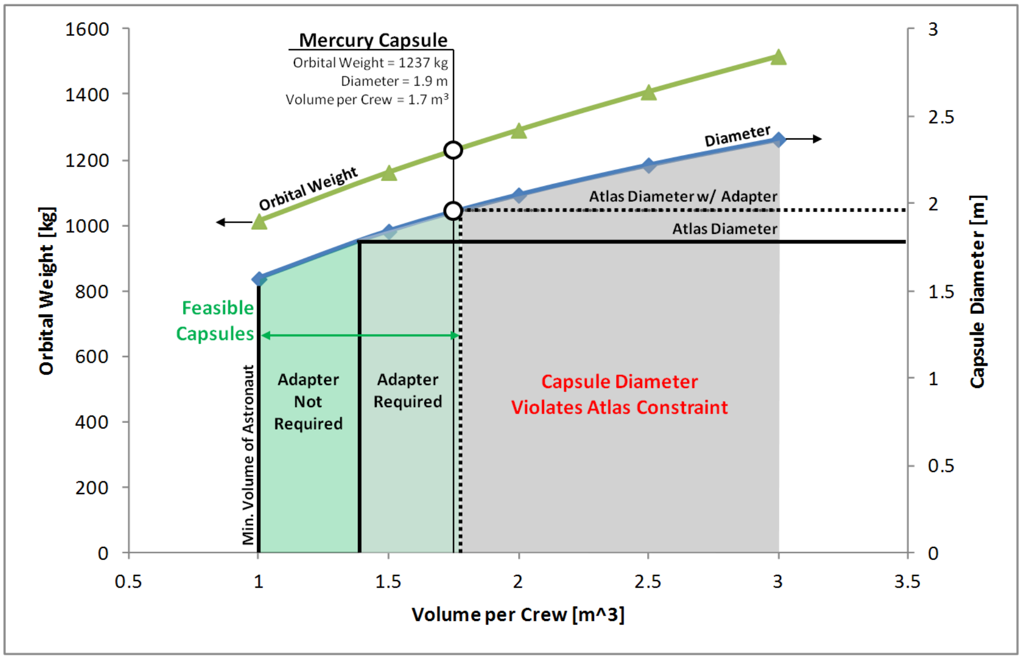


Figure 8. Mercury Capsule Volume per Crew Trade

The starting value of 1 m^3 is a rough estimate of the minimum volume an astronaut-sized human requires. As volume increases, the size and weight increases as expected. When the Atlas booster constraints are overlaid on the capsule results, it can be seen that the Mercury Capsule design point roughly corresponds to the widest vehicle that could fit as payload on the Atlas launcher. An adapter is required for the design point capsule with an increase in diameter of 10% over the standard payload section of Atlas. Increasing the potential adapter size past 10% would further decrease aerodynamic performance during the ascent phase, necessitating development of a more complex payload adapter system. Further, the Atlas maximum payload constraint of 1,400 kg (not shown) will only allow the capsule diameter to grow to 2.2 m; this will limit the design space even if a larger adapter can be adequately designed.

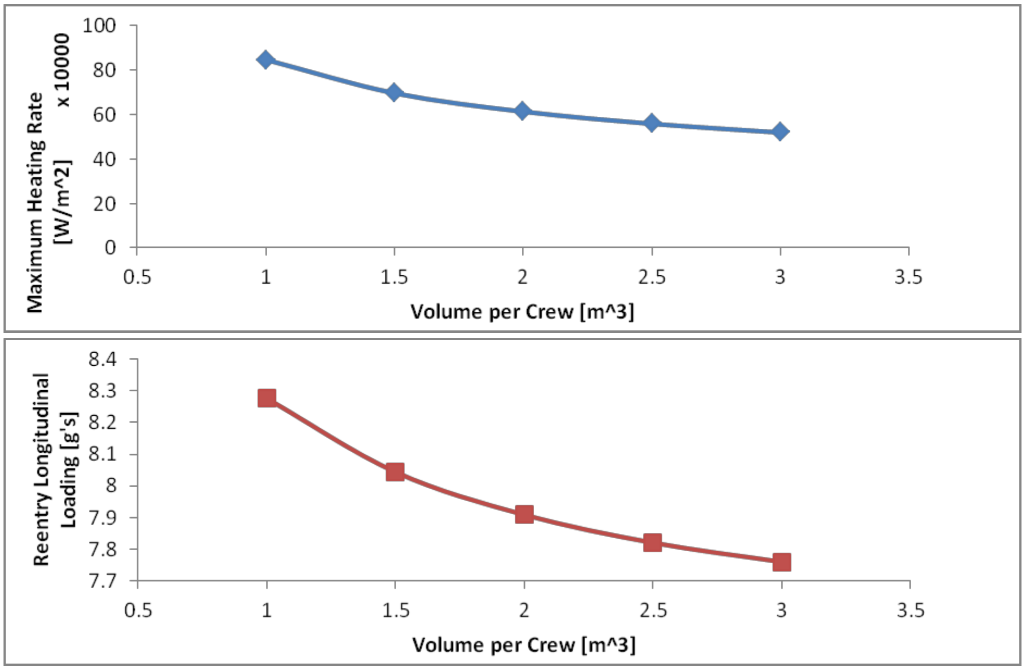


Figure 9. Mercury Capsule Volume per Crew Trade – Performance

Figure 9 shows the trend of heating rate and longitudinal acceleration as part of the same volume per crew trade. The maximum heating constraint of approximately 300 W/cm2 and the maximum loading constraint of 11 g's both appear off the top of each graph. This illustrates that the mission alone has a first order effect on heating and load, while the vehicle configuration choice has only a secondary effect. Still, the trend suggests that the largest possible capsule be selected to minimize undue stress on the thermal protection system and the astronaut.

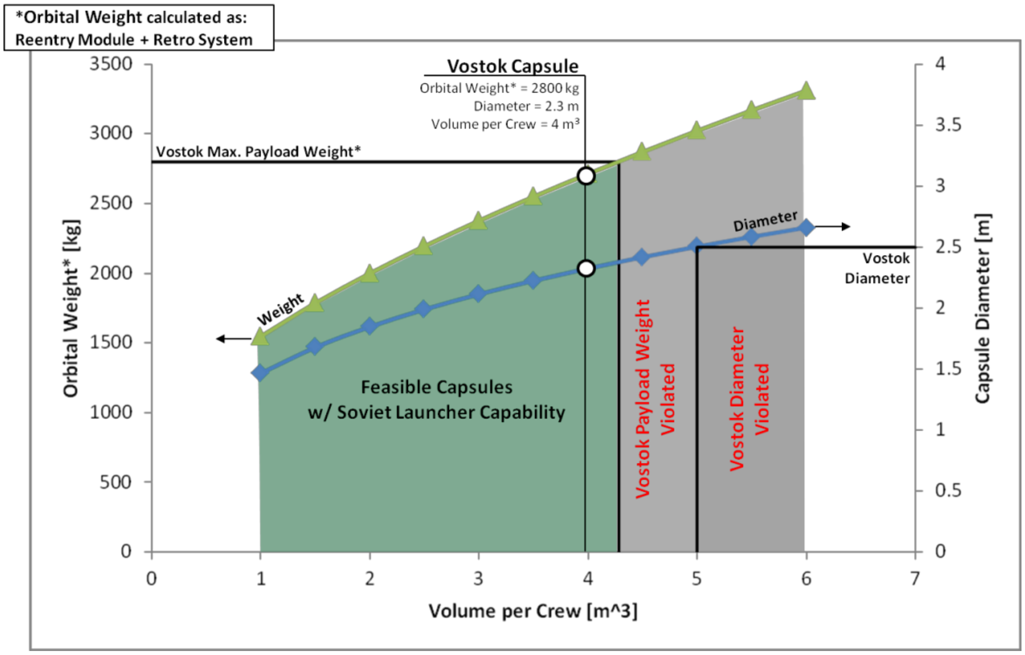


Figure 10. Vostok Capsule Volume per Crew Trade

The Vostok capsule was similarly evaluated in Figure 10. In order to compare systems of the same operational capability, the retro-rocket installed on the service module is modelled as a part of the manned capsule. The reported orbital weight is therefore not the actual orbital weight of Vostok, but the weight of a re-entry module modelled after the Vostok capsule and a retro-rocket propulsion system. It is seen that because of the much larger and more powerful Vostok launcher, a wider portion of the solution space is usable.

The Vostok spherical design has an operational advantage since it is able to re-enter at any attitude. The decrease in complexity is countered by the decrease in re-entry performance, see Figure 11. The trend with increasing vehicle size is the same as Mercury, although the magnitudes are increased. A Mercury-based capsule of the same diameter as a Vostok-based capsule has a larger nose radius (reduced heating) and weighs less (reduced max. acceleration).

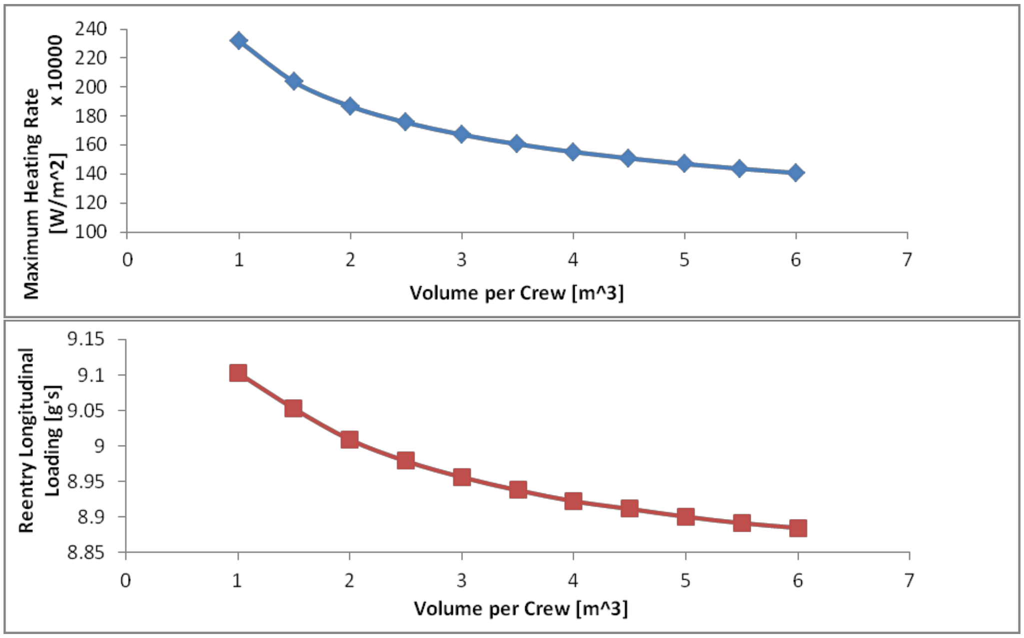


Figure 11. Vostok Capsule Volume per Crew Trade – Performance

By overlaying the results of a spherical geometry with the Mercury capsule geometry design space, novel conclusions can be made, see Figure 12. The design space shows that with the Atlas launch capability available at the time of *Project Mercury*, a purely spherical capsule is not a feasible solution. The sphere is able to fit within the Atlas payload diameter, but the stouter design increases weight past the maximum payload constraint of the existing booster.

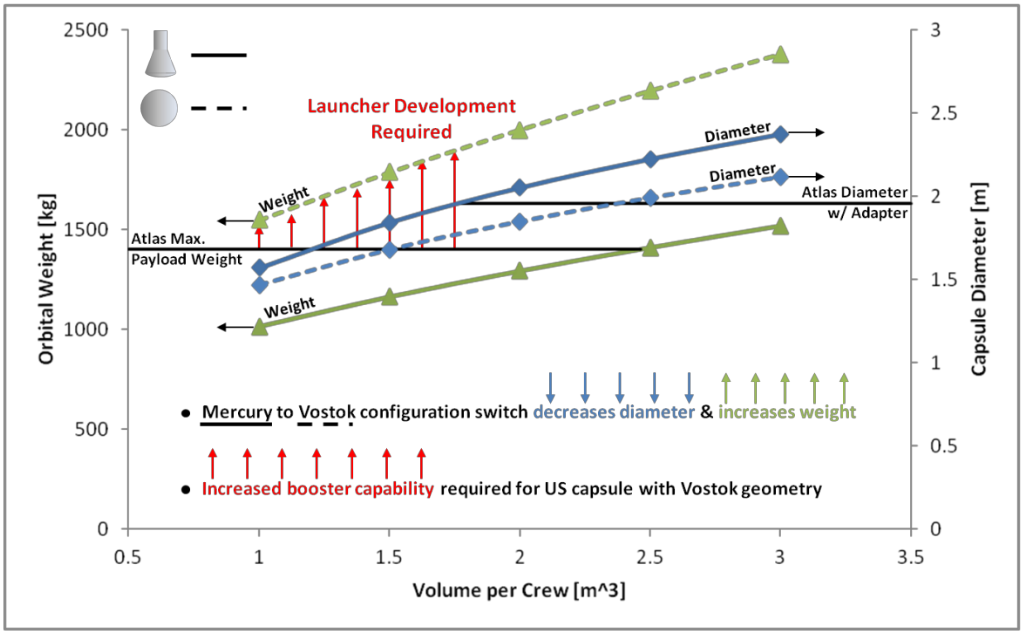


Figure 12. Spherical Geometry Trade

This analysis numerically illustrates that the USA was launcher-constrained in their design possibilities at the time of *Project Mercury*. Because the USSR had invested more heavily into a larger rocket booster system (for nuclear warheads), a more robust spherical capsule was possible. The US manned capsule had to be a smaller vehicle, but at the same time required to have a sufficiently large spherical forward section to handle the re-entry heating environment. This led to the Mercury spherically-capped conical frustrum configuration that maintains a wide spherical heat shield and reduces weight by decreasing useable volume within the capsule.

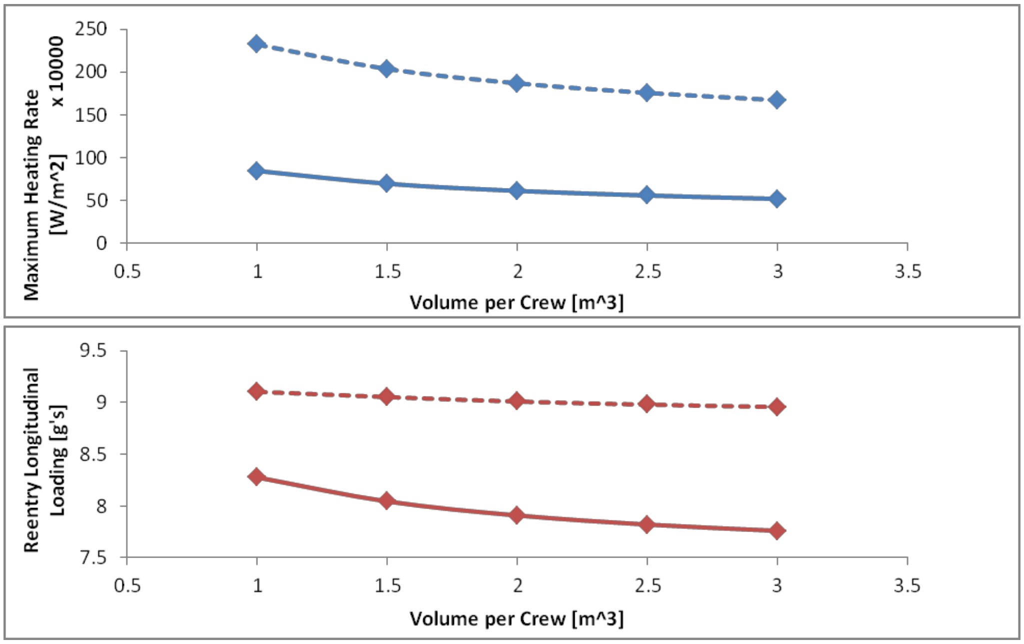


Figure 13. Spherical Geometry Trade – Performance

Launch Vehicle Trades

Booster Height Trade (Redstone)

This section details the build-up of the solution space for the Mercury Redstone Booster. Figure 14 shows the design space for vehicles containing Mercury Redstone level technology levels for aerodynamics, propulsion, and weights. Each point on the figure represents a converged vehicle concept. The design space is visualized through varying the height of the booster and payload mass (mass of re-entry capsule). Height is selected as the independent variable by assuming that the rocket engine selection locks diameter and propulsion performance and therefore total stack height, which is the primary driver for mission performance. The results show that an increase in either booster height or design payload results in an increase in lift-off mass.

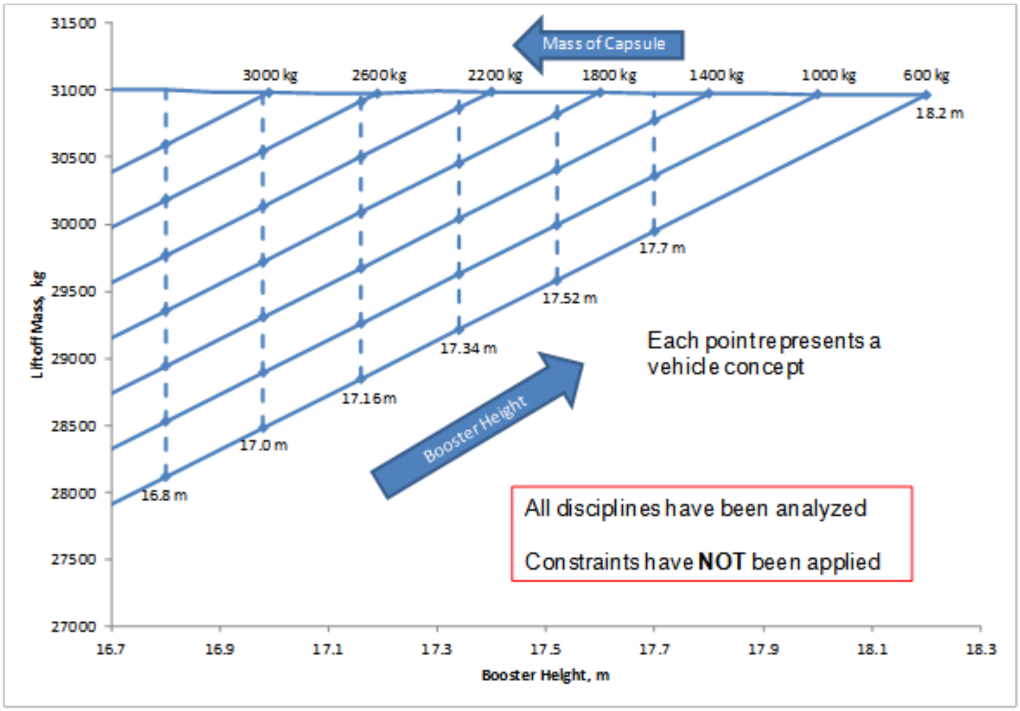
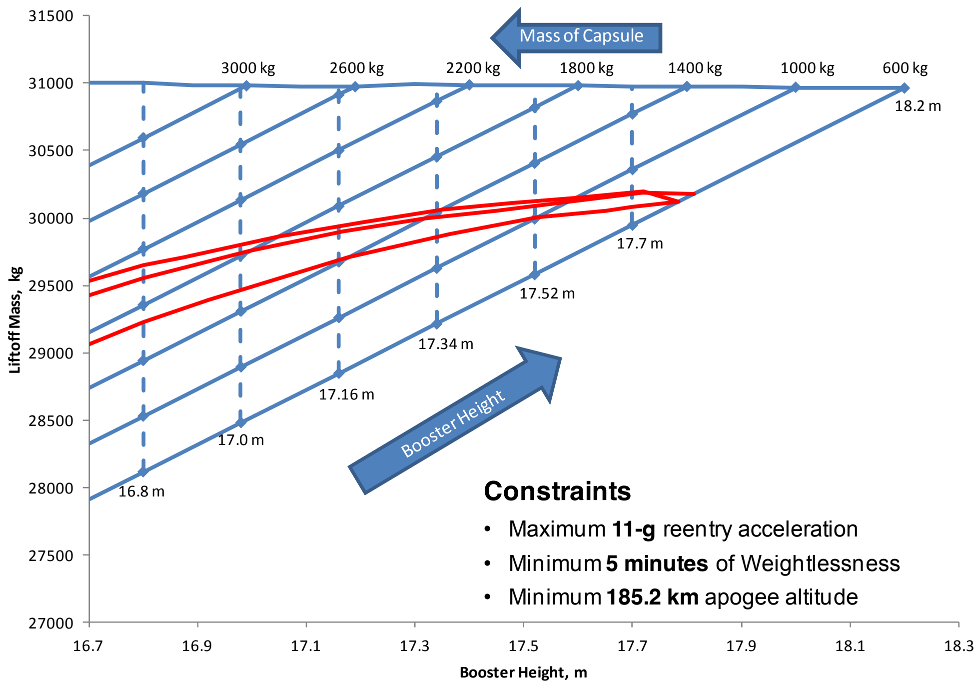


Figure 14. Booster Height Trade – No Constraints

In order to choose a specific vehicle concept or region of applicable vehicle concepts, mission constraints must be applied. The Mercury Redstone mission consisted of three mission constraints:

- Maximum **11-g** deceleration on re-entry
- Minimum **5 Minutes** of Weightless
- Minimum **185.2 km** apogee altitude

The constraints cut through the design space, effectively shrinking the number of vehicle concepts that could feasibly satisfy the mission. It should be noted that the deceleration constraint and the apogee altitude/weightlessness constraint have opposing trends. This means that the parts of the design space that satisfy these constraints are opposing. Anything above the deceleration constraint is feasible, while anything below the apogee altitude/weightlessness constraints is feasible. The result of superimposing all constraints is the highlighting of the feasible solution space for the Mercury Redstone mission, see Figure 16.



Constraints

- Maximum **11-g** reentry acceleration
- Minimum **5 minutes** of Weightlessness
- Minimum **185.2 km** apogee altitude

Figure 15. Booster Height Trade – Constraints Overlaid

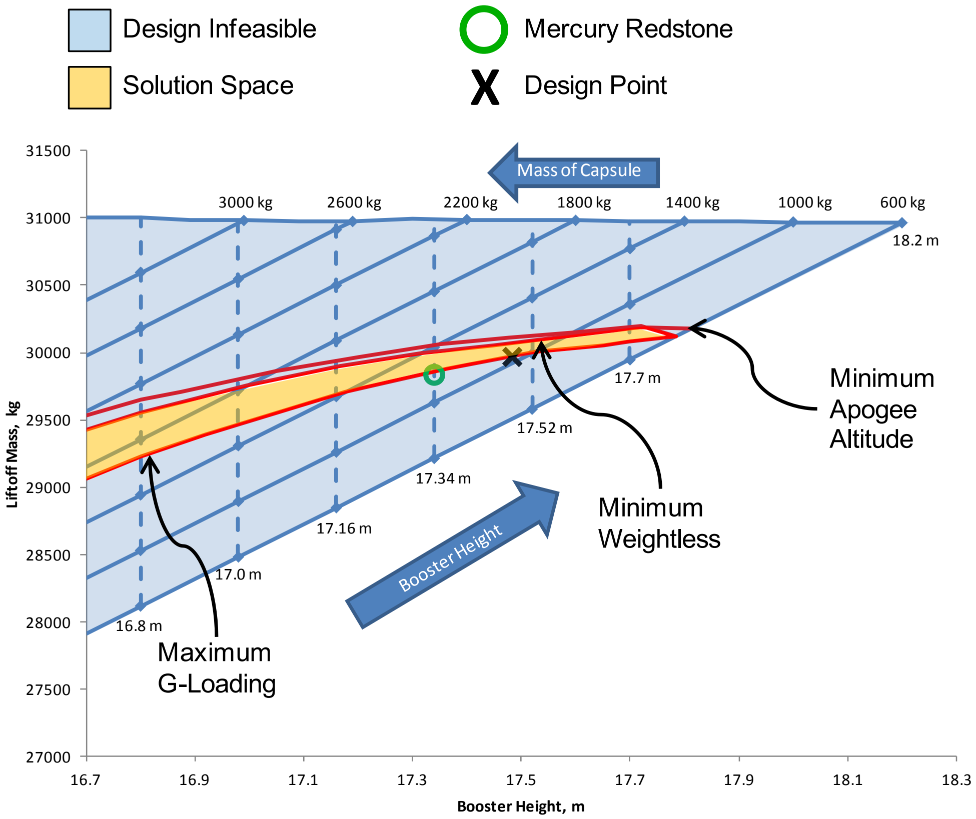


Figure 16. Booster Height Trade – Mercury Redstone Solution Space

Because of the competing nature of the performance constraints, the solution space indicates that the Mercury-Redstone combination has a very small window of feasibility. Since thrust is an independent parameter (locked value), any increase in payload from the design point requires a decrease in launch vehicle size to ensure constant performance. The design point for a Mercury-Redstone launch vehicle lies directly on the maximum g-loading constraint; capsule weight growth results in a mission that does not reach the minimum apogee altitude and/or is not weightless for 5 minutes, while weight reduction from the design point results in a mission that exceeds the safe re-entry loading limits.

Study Conclusions and Follow-On Research

Conclusions

- Capsule and launcher vehicle systems are independently implemented and validated.
- *USAF Space Planners Guide* provides efficient first-order space vehicle sizing guidance.

- Mercury capsule design point is justifiable the largest possible capsule that fits within Atlas launcher constraints.
- Vostok-like spherical geometry not feasible at the time of Project Mercury due to limitations in launcher payload weight capability.
- Redstone launch vehicle is justifiable the smallest feasible booster for fixed Mercury capsule and fixed performance constraints.

Follow-on Research

- Implement analytic models for aerodynamics and heating.
- Adapt structure weight to be dependent on maximum dynamic pressure.
- Adapt thermal protection system weight to be dependent on heating rate / heat load.
- Connect vehicle elements for total system convergence.
- Quantify performance in abort / emergency scenarios.

Project Mercury has been brought to life as a modern case-study example of disciplinary integration and systems level design solution space creation. Historic engineering efforts can be leveraged to gain insight into still-relevant problems and to help today's engineer understand the top-level decision-making of past projects that have pushed the boundaries of multi-disciplinary engineering.

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