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**REUSABLE LAUNCH VEHICLE DESIGN  
IMPLICATIONS FOR REGENERATION TIME**

THESIS

Carlos A. Molina, Lt. Col., Argentine Air Force

AFIT/GLM/ENS/09-08

**DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY**

**AIR FORCE INSTITUTE OF TECHNOLOGY**

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**Wright-Patterson Air Force Base, Ohio**

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AFIT/GLM/ENS/09-08

REUSABLE LAUNCH VEHICLE DESIGN IMPLICATIONS  
FOR REGENERATION TIME

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Logistics Management

Carlos A. Molina, Aeronautical Engineer

Lt. Col., Argentina Air Force

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Abstract

In last few years, the Air Force Research Laboratory sponsored several research projects on a Reusable Launch Vehicles (RLV) whose design, operation, and logistics requirements are intended to be much simpler than for the Space Shuttle. As a part of these efforts, previous researchers developed a model that simulated the post-landing, ground maintenance and prelaunch operations of a RLV in order to evaluate how its design parameters affect the logistics operations. The next logical step is to investigate the effects and interactions of all factors used in the existing simulation model in a single experiment that considers the huge number of possible design characteristics' combinations discovered in the previous studies as well as varying resources such as manpower, ground support equipment and facilities.

The goal of this research is to recommend to the AFRL a preferred design strategy that could minimize the resource requirements in terms of equipment and manpower as well as turnaround time of logistics operations. In order to achieve this goal, this study identifies significant effects of the RLV's design characteristics by utilizing the AFRL's MILEPOST discrete-event simulation model in a systematic design of experiment (DOE) approach. In addition, it assesses the impact of varying resources (manpower, ground support equipment and fleet size) on departure availability.

The results of this research is intended to provide the AFRL with valuable and timely information about the combinations of selected RLV design characteristics which could assist in directing efforts in research and development of the future space vehicle.

AFIT/GLM/ENS/09-08

*To my wife, who offered me unconditional love and support for the last twenty years.*

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Carlos Alberto Molina

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# RESUSABLE LAUNCH VEHICLE DESIGN IMPLICATIONS FOR REGENERATION TIME

## I. Introduction

### Background

In this new century, the United States Air Force's (USAF) need for space capabilities became evident. The advantages these capabilities provide to the Air Force are vital to meeting its mission. Two concepts are developed in USAF's basic doctrine: air and space superiority and air and space supremacy (Martindale, 2006). Air and space superiority is "that degree of dominance that permits friendly land, sea, air, and space forces to operate at a given time and place without prohibitive interference by the opposing force" (AFDD1, 2003). Air and space supremacy is that "degree of superiority wherein opposing air and space forces that are incapable of effective interference anywhere in a given theater of operations" (AFDD1, 2003). Therefore, control and exploitation of space becomes critical to military operations (Servidio, 2008).

The Department of Defense must develop a robust and responsive spacelift capability in order to achieve space superiority (Servidio, 2008). Spacelift capability "delivers satellites, payloads, and materiel to space.... spacelift must be functional and flexible ...timely and responsive..." (AFDD1, 2003). Spacelift can be pursued from two approaches: launching-on-

schedule and launching-on-demand. Responsive spacelift is related to launching-on-demand, and it can be thought as the capability to launch a space vehicle at a moment's notice (Stiegelmeier, 2006).

The National Aeronautics and Space Administration (NASA) developed the Space Shuttle, the only reusable space launch vehicle, as an alternative to expendable launch vehicles, which often had taken weeks or months to prepare for launch. Unfortunately, the Space Shuttle's operational expectations were never met. The number of flights per year was lower than expected because of the complexity and duration of ground operations (McCleskey, 2005).

The future Reusable Launch Vehicle (RLV) is intended to fulfill the requirement of launch-on-demand within a few hours after notice, and for that purpose, minimizing the ground operations is a key issue. An intelligent approach to minimize the logistics footprint during the vehicle operation is to consider the RLV supportability during the design phase.

## **Problem Statement**

In the last few years, the Air Force Research Laboratory (AFRL) sponsored several research projects and theses on the RLV, whose design, operation, and logistics requirements are intended to be much simpler than the Space Shuttle. As part of these efforts, the previous researchers developed a discrete-event simulation model, called Maintenance, Integration, and Launch Pad Operations Simulation and Test (MILEPOST). MILEPOST simulates the post-landing, ground maintenance and pre-launch operations of a RLV, thereby allowing the generation of useful information to evaluate the effects RLV design parameters have on the logistics operations. The logical progression of this research effort is to investigate the effects and interactions of all factors used in the existing simulation model combined into a single

experiment that examines the large number of possible design characteristic combinations discovered in previous studies.

### **Research Objective**

The goal of this research is to recommend a preferred design strategy to the AFRL that could minimize the resource requirements in terms of equipment and manpower as well as turnaround time of logistics operations. The results of this research should provide the AFRL with valuable and timely information about which combination of selected characteristics could help to direct efforts in research and development of the future space vehicle.

### **Research Focus**

The present study identifies relevant design characteristics of the RLV by means of running the AFRL's MILEPOST discrete-event simulation model in a systematic design of experiment (DOE) approach that allows drawing statistical conclusions.

The design characteristics refer to aspects of the RLV design affecting ground operations (recovery, maintenance and prelaunch operations) included in the MILEPOST model. For example, type of fuel (hypergolic or not), type of integration (on pad or off pad), automatic auxiliary power unit (APU) shut down, modular engine, number of motors, etc. are used as design characteristics.

### **Research Questions**

In order to recommend a preferred design strategy to the AFRL, the following research question is addressed:

What combination of RLV design characteristics minimizes the logistics requirements in terms of equipment and manpower as well as turnaround time of ground operations?

To achieve this research, the following investigative questions (IQ) are examined:

**IQ#1:** What are the effects of the design characteristics (design factors) in terms of turnaround time?

**IQ#2:** Which are the most relevant design characteristics that affect turnaround time?

**IQ#3:** What combinations of these factors minimize the logistics footprint?

**IQ#4:** What are the effects of resource constraints in terms of manpower and fleet size on the operational performance?

These questions can be answered using the MILEPOST model in a planned experiment.

The first three questions relate to the logistics footprint in terms of regeneration time for a single vehicle. The last question relates the effects on operational responsiveness of resources constraints. In other words, the answer must explain how the resources levels and fleet size affect the departure availability of the RLVs.

### **Assumptions/Limitations**

Although the model was already validated by its developers, the results obtained from the simulation model cannot be compared to actual data since the RLV does not exist. Analogies from the Space Shuttle, other launch vehicles, and aircraft were used to validate the internal process. Unfortunately, the RLV is still a concept vehicle; therefore, analyses relied heavily on data generated from existing spacecraft and aircraft, which may not accurately represent any system engineered in the actual RLV (Servidio, 2008). Two other limitations are related to the existing simulation model. First, the intended design of experiment uses the actual processes already modeled by the MILEPOST model without any modification; therefore, inaccuracies in

those internal processes may yield inaccurate results. Second, the design of experiment can only include RLV design characteristics which are already considered in the model. Consequently, no other design characteristic other than those considered by the MILEPOST model are included in the experiment. Finally, since the RLV is still a concept vehicle, a high number of possible design characteristics require consideration. This increases the number of possible combinations to the extent where testing all possible combinations becomes infeasible.

### **Implications**

The extent to which the future RLV will achieve the intended performance goals in terms of responsiveness depends on how well the design strategy minimizes the logistics footprint. The conclusions of this research provide designers and decision makers with more insight about how the ground operations will affect the future performance. Accounting for the suggested design characteristics will contribute to the final objective of having a flexible, reliable and responsive spacelift.

### **Summary and Preview**

This chapter provided the incentive and justification for improving regeneration times for future Reusable Launch Vehicles. The objective of this research is to provide suggestions to the AFRL about the characteristics of RLV design that minimize the logistics footprint and also predict the operational responsiveness of the fleet. The research question refers to finding the design characteristics that yield the best results in terms of regeneration time and explaining the effects of resources constraints using MILEPOST. Chapter II provides background information with respect to reusable launch vehicles and previous ground operation simulations performed

during the development of MILEPOST. Chapter III consists of the journal article submitted to JORS, which includes the utilized methodology, findings and conclusions. Chapter IV includes the results of the experiments and the modifications introduced to the simulation model in order to include the ability to deal with fleet size and variable manpower. Chapter V presents the research conclusions and identifies future research opportunities.

## **II. Literature Review**

### **Overview**

The purpose of this review is to provide background information on the research topic and to identify opportunities for improving the current Maintenance, Integration, and Launch Pad Operations Simulation and Test (MILEPOST) discrete-event simulation model created by the Air Force Research Laboratory (AFRL). The review will first provide background information about Reusable Launch Vehicles (RLVs) and then explain the current challenges for the future RLVs. Next, the review presents background information regarding previous ground operations simulation models. Finally, the review narrows its focus, describing MILEPOST, its development, the results of previous studies and suggested research.

### **Background of Reusable Launch Vehicles**

After the Apollo program, NASA focused its efforts in developing Reusable Launch Vehicles (RLV); some examples are the Space Shuttle, National Aerospace Plane, X-33, X-34 and X-37 vehicles. In 1972, Nixon designated the Space Shuttle as the primary future vehicle, expecting it to replace all US medium lift Expendable Launch Vehicles (ELVs) (Smith, 2006). Indeed, the Space Shuttle became a successful RLV, but its regeneration performance was well behind its initially intended goals. After the Challenger accident in 1986, NASA abandoned Nixon's policy and changed its focus back to new ELVs such as Ares-I and Ares-V (Rasky et al., 2006).

Cost, availability, operations rate, and risk are possible causes of the variance between goals and current performance. Historical data indicates that the Space Shuttle operation proved

to be much more expensive than ELVs. In fact, the cost of the Space Shuttle's price per pound to low Earth orbit is about \$10,000/lb (GAO, 1993). This cost represents up to three times the cost of other vehicles such as the Atlas 3B, Atlas 5, Delta 2, Delta 4, Space Falcon 1, Ariane SG, Proton M, Soyuz U, Zenit 3SL, CZ-3B, and PSLV Mk2 (Rasky et. al., 2006).

To be economically competitive, a RLV requires an acceptable flight rate 10 times higher than ELVs (Rasky et. al., 2006). This was not realized by the Space Shuttle; its actual rate was much lower than was expected. In fact, Wilson, Vaughan, Naylor, and Voss demonstrated via simulation that the minimum achievable regeneration time between flights was 28 days (Wilson et. al., 1982). In order to narrow this gap between actual performance and flight expectations, NASA performed some simulation studies in 1999 to evaluate whether increasing the rate from 7 to 15 flights per vehicle per year was economically competitive (Rasky et. al., 2006). During the 1980's, NASA approached this value, but never achieved it (McCleskey, 2005).

One characteristic of a RLV should be that the same vehicle can be sent to space several times before retiring it. Although it is assumed that using the same hardware should avoid fabrication costs, reusability per se cannot guarantee lower costs and higher rates compared to conventional ELVs. It has been argued that "reusability... is only effective if combined with efficient ground and flight operations. Ground operations such as inspection, repair and equipment replacement activities are expected to be the recurrent cost and schedule drivers for future reusable launch vehicles" (Santovincenzo et al., 2005).

Reusability does not necessarily imply low cost; RLVs require more resources during the design, development, and fabrication phases, and more logistics support for ground operations. These ground operations impacted NASA and the Department of Defense (DoD) abilities to meet their space mission responsibilities (Davis, 1988).

In addition, activities related to risk minimization increase the time between flights. For example, the Space Shuttle must complete NASA certification process before every single mission to demonstrate its safety (Hertzfeld, 2000). This certification process implies performing safety inspections that increase the regeneration time.

Currently, the Space Shuttle requires about 3 to 4 months for refurbishing the orbiter between launches (Rooney, 2003). Decreasing this time represents a huge effort that is not practical; thus, NASA scheduled the program for termination in 2010 (Cates and Mollaghasemi, 2005). Although NASA abandoned the idea of improving turnaround times between missions for this specific program, it will surely expect higher flight rates from any new RLV (Rasky et. al., 2006).

### **Challenges for future Reusable Launch Vehicles**

There are economic reasons for diminishing the regeneration time between flights for next generation RLVs; however, the considerations for future military vehicles go beyond costs. U.S. National Space Policy states there is a critical need for assured access-to-space for space assets protection (President, 2006). To meet this policy, the USAF must provide “intelligence, surveillance and reconnaissance of ground targets, deployment and recovery of satellites and rapid constellation replenishment” (Kolodziejcki, 2003).

Satellites provide not only commercial and scientific, but also military applications, as they play a fundamental role in providing military superiority. To protect these assets, the existing fleet of expendable launch vehicles (ELVs) is not as responsive as the future space lift capability requires. The DoD defines the quick response capability as the ability to deliver payloads into orbit in response to National Defense needs. The expected response for a RLV is

defined as the ability to launch within 24 hours of a requirement, and recover and launch again within 24 hours after mission completion (Kolodziejski, 2003). The USAF seeks vehicles that can be quickly regenerated and launched at acceptable costs. The final goal is to spend no more than 8 hours to turnaround the RLV during conflict and up to 48 hours in peacetime (Kolodziejski, 2003).

To achieve this goal, one of the concepts the USAF is studying is the Military Space Plane (MSP). This concept has three components: a reusable space operations vehicle or booster, a reusable space maneuver vehicle, and an array of high utility, military significant payloads. A complete military space system would be defined by this MSP and its operations control center. The MSP should have the capability of accomplishing several space missions and operating on ground in an aircraft like manner (Kolodziejski, 2003).

The USAF determined that the most effective vehicle was a two stage to orbit hybrid with a reusable first stage and expendable second stage. Another intended characteristic of the vehicle is that it should be unmanned, which would reduce the need for several systems aboard associated with human life and its logistics. A fleet of six should be sufficient for initial operations (Kolodziejski, 2003).

The strategic characteristic of this vehicle is that it can be returned to operational status very shortly after landing for rapid response missions (Jacobs et al., 2005). This aspect implies that recovery, maintenance and prelaunch operations should be accomplished faster than required for the Space Shuttle. This is similar to military aircraft ground operations.

The key to decreasing turnaround time is to have a smaller logistics footprint (Rooney and Hartong, 2004). Unfortunately, accuracy of the estimated footprint is limited by lack of information about the future vehicle. Many authors agree that the conceptual model still requires

further research in its planning and design (Jacobs et al., 2005; Johnson et al., 2006; Pope 2006; Stiegelmeier, 2006; Servidio, 2008).

The most economical and timely method for improving ground operations is to consider the future logistics requirements early in the design phase. A large portion of the future logistic effort is committed during this phase; therefore, the real challenge for designers is to wisely choose those aspects of the alternative designs that minimize logistic footprint during the vehicle operation. A design approach that places a premium on operability over performance could minimize or eliminate a number of turnaround functions such as those in the current Space Shuttle operations (McCleskey, 2005). Technology alone cannot assure high flight rates if the logistics footprint cannot be minimized. High-tech devices do not necessarily imply lower and faster maintenance (Rooney, 2003). Thus, the RLV design should consider a RLV that is “flexible, reliable and routinely operable” (Hartong and Rooney, 2004).

### **Previous Ground Operations Simulation Models**

Since the beginning of the Space Shuttle program, many simulation studies which attempted to assess the logistics footprint of the RLV design have been conducted. Wilson et al. (1982) built a discrete event simulation model in Arena® software application called Shuttle Traffic Evaluation Model (STEM); this model was used as a tool to refine the flight scheduling based on more accurate estimation of regeneration flights. Unfortunately, the utility of this program was limited by the lack of historical data (Johnson et al., 2008).

In 2002, Cates, Steele, Mollaghasemi, and Rabaldi presented another simulation model (created with Arena® software) in which ground processing activities data were fit into probability distributions. This NASA sponsored model, with approximately one thousand

modules, was validated using historical data (Cates et al., 2002). Although NASA abandoned the plan of improving the regeneration time between flights before the model was finished, it was used in other scenarios such as mothballing a Shuttle Orbiter or closing Shuttle facilities (Johnson et al., 2008).

Most recently, NASA used the previous simulation experiences to create a model called Manifest Assessment Simulation Tool (MAST) to assess the probability of completing a schedule of planned launches. This model considered orbiter maintenance, vehicle assembly and launch pad operations (Cates and Mollaghasemi, 2005). NASA used MAST to assess the probability of manifest completion before the Space Shuttle retirement in 2010 using Discovery, Atlantis and Endeavour orbiters (Cates and Mollaghasemi, 2005).

At his point, the models were only applicable to one type of vehicle, the Space Shuttle. They described how the launch vehicle affected the logistics footprint after the vehicle had been manufactured; however, the same NASA group of engineers built another model that could assess the logistics footprint before the RLV was manufactured. They wanted a model that enabled engineers to consider the logistics requirements of a new concept vehicle during the design phase. For this purpose, the model had to be flexible and sufficiently generic to allow the assessment of several different alternative designs. NASA developed the Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO) to estimate regeneration times and flight rates. The generic model can be applied to multiple systems and provides a rapid feedback to the designer regarding the operational impact of the design decisions. Having worked on both specific and generic simulations of ground operations, NASA engineers compared the two methods and found that development time is longer and validation is more difficult in the case of the generic model. Once the model is built, though, the time required by

the simulation study is shorter than that required in developing and analyzing the single system simulation (Steele et al, 2002).

The previous ground operations simulation models can be summarized as follows:

**Table 1. RLV simulation models**

Model	Scope	Literature support
Shuttle Traffic Evaluation Model (STEM)	Specific for Space Shuttle	Wilson <i>et al.</i> , 1982
Space Shuttle Modeling	Specific for Space Shuttle	Cates <i>et al.</i> , 2002
Manifest Assessment Simulation Tool (MAST)	Specific for Space Shuttle	Cates and Mollaghasemi, 2005
Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO)	Generic	Steele et al, 2002

## **MILEPOST Development**

### ***Origin***

The AFRL developed the Space Access Vehicles Mission and Operations Simulation (SAVMOS) to assess MSP concepts. SAVMOS is a computer simulation environment designed for modeling a MSP and its operations system. This model initially intended to study the performance of experimental aircraft like X-37/42 and conceptual hypersonic vehicles (Jacobs et al., 2005). Currently, it can assess preparation for flight, launch and space maneuvers, military operational missions, return to earth, and the preparation for the next cycle of performance (Jacobs et al., 2005).

SAVMOS considers the following systems: 1) Integrated Development & Operations Systems (IDOS), 2) Virtual Battlespace Management System (VBMS), 3) Space Operations Simulator (SOPsSI), 4) Space Maneuver Vehicle Operations (SMVOps) and 5) Ground Operations (Jacobs et al., 2005).

By 2006, SAVMOS had not achieved an acceptable capability of modeling ground-based operations. The AFRL sponsored the Air Force Institute of Technology (AFIT) to develop a method for assessing the ground operations of the MSP. As a result, AFIT developed a model that studied post-flight recovery, maintenance, and pre-launch activities necessary for subsequent missions (Johnson et al., 2006). The model was called Maintenance, Integration, and Pad Simulation and Test (MILEPOST). Currently, MILEPOST is a part of SAVMOS (Johnson et al., 2008), providing it with logistics information necessary to evaluate candidate designs..

### *Description*

MILEPOST is a discrete-event simulation model that can evaluate candidate RLV recovery, maintenance, and pre-launch operations by simulating the regeneration time required for any specific vehicle design (Martindale, 2006; Pope, 2006; Stiegelmeier, 2006). The most important characteristic of MILEPOST is that the same simulation model can be used to assess logistic impact of different designs avoiding the need of building separate models for each specific design.

Using MILEPOST, designers can perform tradeoff studies on the impact of design characteristics on regeneration time and support personnel requirements. More than 50,000 distinct designs (or configurations) can be evaluated (by changing the number of motors, type of fuels, surface area of thermal protection systems, and more than 30 other design characteristics) without having to modify the model (Johnson et al., 2008). A Graphic Unit Interface (GUI) built into MILEPOST allows the users to easily tailor any specific model (Pope, 2006; Stiegelmeier, 2006).

The MILEPOST model is similar to NASA's GEMFLO model in that both are generic models and can assess different designs. Additionally, they are built with the same software

application and use the same approach to studying ground activities. They differ in that MILEPOST decomposes the ground operations into recovery, maintenance and prelaunch activities with much greater detail than GEMFLO (Johnson et al., 2008), because military missions for the future RLV are expected to be much more time sensitive. For example, whereas MAST was used to assess the probability of accomplishing 28 missions in almost 6 years by 3 orbiters (Cates and Mollaghasemi, 2005), military “rapid response” requirements are concerned with the probability of accomplishing missions in 48 hours (Rooney, 2003).

Even though the MILEPOST is generic, it still requires some basic assumptions. First, the model assumes the vehicle is unmanned. Second, it assumes the vehicle is a Hybrid Launch Vehicle, with a reusable first stage and expendable second stage. Finally, it assumes that the RLV launches vertically and lands horizontally (Johnson et al., 2006; Michalski & Johnson, 2007).

The problem with developing a generic model is that the vehicle does not yet exist; therefore, recovery, maintenance, and prelaunch operations sequences of the future RLV should be based on real systems that best approach the method by which the RLV will be operated and maintained (Steele et al., 2002). Thus, during the development of MILEPOST, the challenge for USAF simulation engineers was to select adequate aircraft and spacecraft with similar logistics requirements to the future RLV (Johnson et al., 2008).

Operation sequences set in the model are based on the Space Shuttle, Delta IV, Atlas IV, Minuteman III, Zenit 3SL, B-2 Bomber, and F-16 fighter. Undoubtedly, the Space Shuttle was chosen because it is the only RLV in operation. Atlas V and Delta IV were recently added to the U.S. ELVs fleet and have the most advanced technology. The Zenit 3SL was designed for quick prelaunch operations. The B-2 represents the most recent U.S. heavy load-capable aircraft; in

addition to its complexity, its usage rate is similar to a RLV. Finally, the F-16 provides more knowledge on how quickly the RLV might be recovered for the next mission (Martindale, 2006; Johnson et al., 2006; Pope, 2006; Stiegelmeier, 2006).

Using these aircraft and spacecraft, the USAF engineers modeled MILEPOST ground operations which can be grouped in three sub-models: 1) Post landing operations, 2) Ground Maintenance operations and 3) Pre-launch operations. The three sub-models are discrete-event simulations developed in Arena®. While working simultaneously, the developers considered that the three sub-models must be compatible and use the same basic assumptions about the RLV. Additionally, two of the researches, Pope (2006) and Stiegelmeier (2006), worked together to developed a common Graphic Unit Interface (GUI) that allows the user to tailor design characteristics. After completion, the sub-models were assembled in the same simulation model.

### ***Ground Maintenance Operations Modeling***

Pope (2006) constructed a sub-model that represents the logical sequence of expected maintenance tasks of a RLV and estimates the total maintenance duration. In order to construct the model, he identified the generic functions of RLV maintenance and compared them to several military aircraft, ELVs, and the Intercontinental Ballistic Missile (ICBM). He also identified design drivers that affect type and duration of maintenance operations and included them in the model.

A Delphi panel of 19 experts ensured that Pope's model captured the best maintenance flow representing a reusable maintenance cycle. The members were chosen from different

maintenance fields, such as B-2, IBCM, and Air Combat Command. They validated not only this sub-model but also the other two components of MILEPOST (Pope, 2006).

Pope completed his model for assessing RLV design characteristics and found that when two motors are used, increasing the efficiency in the thermal protection system (TPS) would have the greatest impact on the overall processing time. When more than two motors are used, the motor maintenance processes are more influential than TPS maintenance (Pope, 2006). Pope experimented with the model in a limited manner; only three configurations were studied. More experimentation with the model could present important findings.

Unfortunately, this model has limitations. First, the data used for simulating processing times of single activities was notional. This means that process times are based on educated guesses from experts instead of using parametric relationships. Second, the model was unconstrained by quantity or quality of resources; therefore, manpower requirements did not affect the results of the model. Finally, MILEPOST could only model one launch vehicle per run. For these reasons, he suggested that future studies should analyze the sensitivity of sortie production versus resource levels, and compare scheduled RLV missions to sortie production (Pope, 2006).

### ***Prelaunch Operations Modeling***

Stiegelmeier's (2006) work focused on a very important aspect of vehicle regeneration: vehicle handling and servicing, also known as pre-launch operations. Stiegelmeier's model, the second MILEPOST sub-model, grouped pre-launch operations into payload integration, stage mating, vehicle transport and servicing.

The designed experiment did not yield an exact estimate of RLV regeneration time, but rather provided preliminary insights considering prelaunch operation options, such as second stage pre-integration and integration orientation (vertical vs. horizontal). As a conclusion of his study, he suggested some design strategies to minimize prelaunch operation time: pre-integration, integration off launch pad, horizontal orientation, and parallel propellant loading (Stiegelmeier, 2006).

In his suggestions for future research, he states that it would be worthwhile to use a computer simulation to analyze how different combinations of numbers of facilities, launch pads, first and second stages and other resources affect regeneration time and sortie rate. Since the performed experiment analyzed only one isolated processing decision, he recommended performing more experiments to study the impact of two or more processing decisions at the same time (Stiegelmeier, 2006).

### ***Recovery Operations Modeling***

Martindale (2006) modeled the third sub-model of MILEPOST. For modeling the recovery activities, he studied mainly the Space Shuttle and F-16 recovery processes, with a logical emphasis on the orbiter due to the unique nature of future RLV. The comparison of F-16 and Space Shuttle Orbiter explained the need of adapting not only to the space system requirements, but also to the USAF goals in terms of rapid response.

As a result of his study, he found that automation (for example, for hazardous gas detection) and special handling requirements avoidance are key factors in reducing recovery process duration. He also found that, although sequences of post-flight activities between Space

Shuttle and F-16 are similar, they vary greatly in complexity and duration. Martindale did not perform experiments to evaluate alternative design as part of his research (Martindale, 2006).

The development of the basic model can be summarized in the following table.

**Table 2. RLV simulation studies**

Model	Focus	Literature Support
Space Access Vehicles Mission and Operations Simulation (SAVMOS)	RLV preparation for flight, launch and space maneuvers, military operational missions, return to earth, and the preparation for the next cycle	Jacobs et al., 2005
Maintenance, Integration, and Pad Simulation and Test (MILEPOST)	Maintenance Operations	Pope, 2006
	Pre-launch Operations	Stiegelmeier, 2006
	Recovery Operations	Martindale, 2006

### **Studies performed using MILEPOST**

#### ***Process Time Refinement***

The following RLV studies followed two main objectives: 1) To improve the model fidelity and 2) To gain insight of ground operations using the recently built model. As Johnson et al. (2006) stated, a portion “of the following research steps will use the model to estimate the relationships between regeneration time and probable design configurations, using notional but plausible process times.”

Servidio’s research was related to the first objective: to improve model fidelity. Using Pope’s research suggestions, he attempted to improve the process time estimation by replacing the educated notional approach with parametric relationship between maintenance factors and process times (Pope, 2006). Using USAF Reliability and Maintainability Information System (REMIS) data, Servidio established regression models for more than 60% of the maintenance activities; however, he suggested that further analysis is needed to establish parametric relationships for the rest of the activities where the regression models could not be built (Servidio, 2008).

### *Manpower Requirements and Organizational Assessment*

For the second objective of gaining insight into ground operations using the model) many studies were performed (Johnson et al, 2006; Michalski, 2007; Michalski and Johnson, 2007; Michalski and Johnson 2008; Johnson and Jackson 2008, Johnson et al, 2008). Although the baseline MILEPOST model assumes unconstrained resources, it is evident that resource utilization plays a fundamental role in trade-off evaluations. Michalski (2007) estimated a baseline of logistics manpower requirements for ground support of a RLV. She determined that the USAF B-2 Bomber Maintenance Group (MXG) and Logistics Readiness Squadron (LRS) provided the organizational structure that would best support regeneration operations for an RLV fleet. The requirements are expected to vary between approximately 1,200 and 2,400 personnel with a most likely value of 1,900 personnel for a 24-hour operation of six RLVs (Michalski and Johnson, 2007).

In addition, Michalski and Johnson conducted individual studies of the impact of specific characteristics in manpower requirements. For example, a Thermal Protection System similar to the Space Shuttle will increase maintenance support requirements by 30% of the established baseline, and an Integrated Vehicle Health Management system could reduce the manpower requirements by 40% (Michalski and Johnson, 2007).

In 2008, Michalski and Johnson continued their studies about the military organizational structure that would best support the future RLV. They suggested two options: 1) a Logistics Readiness Squadron under the Mission Support Group or 2) a Maintenance Group that includes an RLV maintenance squadron for flight line support, a Maintenance Squadron for backshop support, a Maintenance Operations Squadron, and a Munitions Squadron. They stated that more

research is needed to estimate facilities, equipment, and materiel resources (Michalski and Johnson, 2008).

### ***Modeling Regeneration Time and Ground Support Manpower for a RLV***

Air Force simulation engineers performed several runs of the MILEPOST model to gain additional insight of design decisions regarding the manpower requirements increasing the number of decision factors. They considered a design in which 21 design decisions were fixed at pre-established values and performed a simulation experiment varying three ground operations alternatives: pre-integration, integration on pad and orientation (Johnson et al., 2008).

They established the initial manpower level by running the model with unconstrained resources to assess the maximum requirement for each technical specialty and deemed it as the manpower baseline. Next, they evaluated the design at different levels of the baseline. They found that increasing the manpower can only improve regeneration time up to a certain level, but additional time savings must come from vehicle design characteristics (Johnson et al., 2008).

One limitation of their work is that they did not consider the effect of successive, possibly overlapping, RLV missions on resource constraints, queuing behaviors or regeneration time. They also suggested that new studies should focus on staffing, operations and support cost (Johnson et al., 2008).

### ***Other studies regarding future RLV support***

In 2008, Johnson and Jackson studied other aspects related to the life cycle ground support staffing for the RLV, assuming a six vehicles fleet, continuous operations and beddown at an existing Air Force Base (Johnson and Jackson, 2008). They found that 1) the maintenance

group would range from 400 to 2400 personnel, depending on fleet size, health management systems, thermal protection technology, and vehicle size, and 2) the associated personnel cost would range from under \$80 million to \$160 million per year. They suggested that the USAF must decide whether it will proceed with the RLV program in the same contractor-conducted manner as was used for previous space launch systems or instead migrate its space systems ground support toward historical organic aircraft operations and sustainment processes (Johnson and Jackson, 2008).

### **Relationships between previous studies and this research**

The reviewed simulation studies using MILEPOST, including those studies done accomplished during its development, demonstrate that the model can yield information that has not been exploited yet. Thus far, the studies considered some fixed design factors and varied others to gain insight of the design, but ignored many possible interactions. In addition, the current model does not consider queuing effects; therefore, it cannot evaluate the impact of fleet size on regeneration time. The focus of the present research will be placed on both aspects: 1) performing a single experiment in which all the factors in the model and interactions between them are considered and 2) expanding the model capabilities to deal with queuing effects of the fleet size. Table 3 summarizes the relationships between suggested research reviewed and this research.

**Table 3. Relationships between suggested and present research.**

MILEPOST DEVELOPMENT			
Literature Review	Focus of simulation Study	Recommended research	Considered by this research?
Pope, 2006	Maintenance Operations	Analyze the sensitivity of sortie production versus resource levels	YES
		Compare scheduled RLV missions to sortie production	YES
Stiegelmeier, 2006	Prelaunch Operations	Analyze how different combinations of resources would affect regeneration time and sortie rate.	YES
		Perform more experiments to study the impact of two or more processing decisions at the same time	YES
Martindale, 2006	Recovery Operations	Include the impact of RLV designs to the cost of operations	NO
		Perform more experiments	YES
Johnson et. al, 2006	Regeneration Time between Flights	Estimate the relationships between regeneration time and probable design configurations, using notional but plausible process times	NO
		Integrate MILEPOST into SAVMOS	NO
		Improve the manpower fidelity in terms of skills	NO
		Analyze USAF organizations to provide adequate ground support	NO
Milchasky, 2007	Logistics Manpower requirements for Ground Support	Estimate facilities, equipment, and materiel resources	NO
Milchasky and Johnson, 2007	Logistics Manpower requirements for Ground Support	Estimate facilities, equipment, and materiel resources	NO
Milchasky and Johnson, 2008	Support organization structure	Estimate organization structure, personnel numbers, and associated total life cost	NO
Servidio, 2008	Process Time Refinement	Establish parametric relationships for the all ground activities	NO
Johnson et. al, 2008	Regeneration Time and Ground Support Manpower	Consider the effect of successive, possible overlapping RLV missions on resource constraints, queuing behaviors	YES
		Next phase should focus on staffing, operations and support cost	NO
Johnson and Jackson, 2008	Life Cycle Ground Support Staffing	Compare long-term outsourcing versus organic ground support	NO

## Summary

This chapter provided background information with respect to RLV ground operations simulations and identified opportunities for improving the current MILEPOST model created by AFRL. The first two sections discussed RLV challenges, addressing the importance of small logistics footprint as a key factor for improving regeneration times between flights. The second section discussed the previous ground operations simulation studies regarding RLV and

highlighted the benefit of having a generic simulation tools for assessing ground operations.

After this, the review conducted a thorough analysis of MILEPOST development, identifying limitations and scopes of previous studies. As a result of this review two research opportunities were identified: 1) To perform a single complete experiment and 2) To add queuing capabilities to the current model.

### **III. Journal Article**

#### **Overview**

This chapter consists of the article manuscript that is in process of submission to the Journal of Operational Research Society. This manuscript includes the abstract, the introduction, methodology, findings and conclusions.

#### **Abstract**

In the last few years, the Air Force Research Laboratory (AFRL) sponsored several research projects on a Reusable Launch Vehicle (RLV) whose design, operation, and logistics requirements are intended to be much simpler than for the Space Shuttle. As part of these efforts, the previous researchers developed a discrete-event simulation model, called Maintenance, Integration, and Launch Pad Operations Simulation and Test (MILEPOST), that simulates the post-landing, ground maintenance and pre-launch operations of a RLV generating useful information to evaluate how RLV design parameters affect the logistics operations. The present study identifies significant effects of the RLV's design characteristics by means of running the AFRL's MILEPOST model in a systematic design of experiment (DOE) approach. In addition, it assesses the impact of varying resources (manpower, ground support equipment and fleet size) on departure availability.

#### **Introduction**

In this new century, the United States Air Force's (USAF) need for space capabilities became evident. The advantages these capabilities provide to the Air Force are vital to meeting its mission. Two concepts are developed in USAF's basic doctrine: air and space superiority and

air and space supremacy (Martindale, 2006). Air and space superiority is “that degree of dominance that permits friendly land, sea, air, and space forces to operate at a given time and place without prohibitive interference by the opposing force” (AFDD1, 2003). Air and space supremacy is that “degree of superiority wherein opposing air and space forces that are incapable of effective interference anywhere in a given theater of operations” (AFDD1, 2003). Therefore, control and exploitation of space becomes critical to military operations (Servidio, 2008).

The Department of Defense must develop a robust and responsive spacelift capability in order to achieve space superiority (Servidio, 2008). Spacelift capability “delivers satellites, payloads, and materiel to space.... spacelift must be functional and flexible ...timely and responsive...” (AFDD1, 2003). Spacelift can be pursued from two approaches: launching-on-schedule and launching-on-demand. Responsive spacelift is related to launching-on-demand, and it can be thought as the capability to launch a space vehicle at a moment’s notice (Stiegelmeier, 2006).

The National Aeronautics and Space Administration (NASA) developed the Space Shuttle, the only reusable space launch vehicle, as an alternative to expendable launch vehicles which often had taken weeks or months to prepare for launch. Unfortunately, the Space Shuttle’s operational expectations were never met. The number of flights per year was lower than expected because of the complexity and duration of ground operations (McCleskey, 2005).

The future Reusable Launch Vehicle (RLV) is intended to fulfill the requirement of launch-on-demand within a few hours after notice, and for that purpose, minimizing the ground operations is a key issue. An intelligent approach to minimize the logistics footprint during the vehicle operation is to consider the RLV supportability during the design phase.

In the last few years, the Air Force Research Laboratory (AFRL) sponsored several research projects and theses on the RLV, whose design, operation, and logistics requirements are intended to be much simpler than the Space Shuttle. As part of these efforts, the previous researchers developed a discrete-event simulation model, called Maintenance, Integration, and Launch Pad Operation Simulation and Test (MILEPOST). MILEPOST simulates the post-landing, ground maintenance and pre-launch operations of a RLV, thereby allowing the generation of useful information to evaluate the effects RLV design parameters have on the logistics operations. The logical progression of this research effort is to investigate the effects and interactions of all factors used in the existing simulation model combined into a single experiment that examines the large number of possible design characteristic combinations discovered in previous studies.

The goal of this research is to recommend a preferred design strategy to the AFRL that could minimize the resource requirements in terms of equipment and manpower as well as turnaround time of logistics operations. The results of this research should provide the AFRL with valuable and timely information about which combination of selected characteristics could help to direct efforts in research and development of the future space vehicle.

The present study identifies relevant design characteristics of the RLV by means of running the AFRL's MILEPOST discrete-event simulation model in a systematic design of experiment (DOE) approach that allows drawing statistical conclusions.

The design characteristics refer to aspects of the RLV design affecting ground operations (recovery, maintenance and prelaunch operations) included in the MILEPOST model. For example, type of fuel (hypergolic or not), type of integration (on pad or off pad), automatic

auxiliary power unit (APU) shut down, modular engine, number of motors, etc. are used as design characteristics.

In order to recommend a preferred design strategy to the AFRL, the following research question is addressed:

*What combination of RLV design characteristics minimizes the logistics requirements in terms of equipment and manpower as well as turnaround time of ground operations?*

To achieve this research, the following investigative questions (IQ) are examined:

*IQ#1: What are the effects of the design characteristics (design factors) in terms of turnaround time?*

*IQ#2: Which are the most relevant design characteristics that affect turnaround time?*

*IQ#3: What combinations of these factors minimize the logistics footprint?*

*IQ#4: What are the effects of resource constraints in terms of manpower and fleet size on the operational performance?*

These questions can be answered using the MILEPOST model in a planned experiment.

The first three questions relate to the logistics footprint in terms of regeneration time for a single vehicle. The last question relates the effects on operational responsiveness of resources constraints. In other words, the answer must explain how the resources levels and fleet size affect the departure availability of the RLVs.

#### *Assumptions/Limitations*

Although the model was already validated by its developers, the results obtained from the simulation model cannot be compared to actual data since the RLV does not exist. Analogies from the Space Shuttle, other launch vehicles, and aircraft were used to validate the internal process. Unfortunately, the RLV is still a concept vehicle; therefore, analyses relied heavily on data generated from existing spacecraft and aircraft, which may not accurately represent any

system engineered in the actual RLV (Servidio, 2008). Two other limitations are related to the existing simulation model. First, the intended design of experiment uses the actual processes already modeled by the MILEPOST model without any modification. Therefore, inaccuracy in those internal processes may yield inaccurate results. Second, the design of experiment can only include RLV design characteristics that are already considered in the model. Consequently, no other design characteristic than those considered by the MILEPOST model are included in the experiment. Finally, since the RLV is still a concept vehicle, a high number of possible design characteristics require consideration. This increases the number of possible combinations to the extent where testing all possible combinations becomes infeasible.

The extent to which the future RLV will achieve the intended performance goals in terms of responsiveness depends on how well the design strategy minimizes the logistics footprint. The conclusions of this research provide designers and decision makers with more insight about how the ground operations will affect the future performance. Accounting for the suggested design characteristics will contribute to the final objective of having a flexible, reliable and responsive spacelift.

## **Background**

After the Apollo program, NASA focused its efforts in developing Reusable Launch Vehicles (RLV); some examples are the Space Shuttle, National Aerospace Plane, X-33, X-34 and X-37 vehicles. In 1972, Nixon designated the Space Shuttle as the primary future vehicle, expecting it to replace all US medium lift Expendable Launch Vehicles (ELVs) (Smith, 2006). Indeed, the Space Shuttle became a successful RLV, but its regeneration performance was well behind its initially intended goals. After the Challenger accident in 1986, NASA abandoned

Nixon's policy and changed its focus back to new ELVs such as Ares-I and Ares-V (Rasky et al., 2006).

Cost, availability, operations rate, and risk are possible causes of the variance between goals and current performance. Historical data indicates that the Space Shuttle operation proved to be much more expensive than ELVs. In fact, the cost of the Space Shuttle's price per pound to low Earth orbit is about \$10,000/lb (GAO, 1993). This cost represents up to three times the cost of other vehicles such as the Atlas 3B, Atlas 5, Delta 2, Delta 4, Space Falcon 1, Ariane SG, Proton M, Soyuz U, Zenit 3SL, CZ-3B, and PSLV Mk2 (Rasky et. al., 2006).

To be economically competitive, a RLV requires an acceptable flight rate 10 times higher than ELVs (Rasky et. al., 2006). This was not realized by the Space Shuttle; its actual rate was much lower than was expected. In fact, Wilson, Vaughan, Naylor, and Voss demonstrated via simulation that the minimum achievable regeneration time between flights was 28 days (Wilson et. al., 1982). In order to narrow this gap between actual performance and flight expectations, NASA performed some simulation studies in 1999 to evaluate whether increasing the rate from 7 to 15 flights per vehicle per year was economically competitive (Rasky et. al., 2006). During the 1980's, NASA approached this value, but never achieved it (McCleskey, 2005).

One characteristic of a RLV should be that the same vehicle can be sent to space several times before retiring it. Although it is assumed that using the same hardware should avoid fabrication costs, reusability per se cannot guarantee lower costs and higher rates compared to conventional ELVs. It has been argued that "reusability... is only effective if combined with efficient ground and flight operations. Ground operations such as inspection, repair and equipment replacement activities are expected to be the recurrent cost and schedule drivers for future reusable launch vehicles" (Santovincenzo et al., 2005).

Reusability does not necessarily imply low cost; RLVs require more resources during the design, development, and fabrication phases, and more logistics support for ground operations. These ground operations impacted NASA and the Department of Defense (DoD) abilities to meet their space mission responsibilities (Davis, 1988).

In addition, activities related to risk minimization increase the time between flights. For example, the Space Shuttle must complete NASA certification process before every single mission to demonstrate its safety (Hertzfeld, 2000). This certification process implies performing safety inspections that increase the regeneration time.

Currently, the Space Shuttle requires about 3 to 4 months for refurbishing the orbiter between launches (Rooney, 2003). Decreasing this time represents a huge effort that is not practical; thus, NASA scheduled the program for termination in 2010 (Cates and Mollaghasemi, 2005). Although NASA abandoned the idea of improving turnaround times between missions for this specific program, it will surely expect higher flight rates from any new RLV (Rasky et al., 2006).

### *Challenges for future Reusable Launch Vehicles*

There are economic reasons for diminishing the regeneration time between flights for next generation RLVs; however, the considerations for future military vehicles go beyond costs. U.S. National Space Policy states there is a critical need for assured access-to-space for space assets protection (President, 2006). To meet this policy, the USAF must provide “intelligence, surveillance and reconnaissance of ground targets, deployment and recovery of satellites and rapid constellation replenishment” (Kolodziejcki, 2003).

Satellites provide not only commercial and scientific, but also military applications, as

they play a fundamental role in providing military superiority. To protect these assets, the existing fleet of expendable launch vehicles (ELVs) is not as responsive as the future space lift capability requires. The DoD defines the quick response capability as the ability to deliver payloads into orbit in response to National Defense needs. The expected response for a RLV is defined as the ability to launch within 24 hours of a requirement, and recover and launch again within 24 hours after mission completion (Kolodziejcki, 2003). The USAF seeks vehicles that can be quickly regenerated and launched at acceptable costs. The final goal is to spend no more than 8 hours to turnaround the RLV during conflict and up to 48 hours in peacetime (Kolodziejcki, 2003).

To achieve this goal, one of the concepts the USAF is studying is the Military Space Plane (MSP). This concept has three components: a reusable space operations vehicle or booster, a reusable space maneuver vehicle, and an array of high utility, military significant payloads. A complete military space system would be defined by this MSP and its operations control center. The MSP should have the capability of accomplishing several space missions and operating on ground in an aircraft like manner (Kolodziejcki, 2003).

The USAF determined that the most effective vehicle was a two stage to orbit hybrid with a reusable first stage and expendable second stage. Another intended characteristic of the vehicle is that it should be unmanned, which would reduce the need for several systems aboard associated with human life and its logistics. A fleet of six should be sufficient for initial operations (Kolodziejcki, 2003).

The strategic characteristic of this vehicle is that it can be returned to operational status very shortly after landing for rapid response missions (Jacobs et al., 2005). This aspect implies

that recovery, maintenance and prelaunch operations should be accomplished faster than required for the Space Shuttle. This is similar to military aircraft ground operations.

The key to decreasing turnaround time is to have a smaller logistics footprint (Rooney and Hartong, 2004). Unfortunately, accuracy of the estimated footprint is limited by lack of information about the future vehicle. Many authors agree that the conceptual model still requires further research in its planning and design (Jacobs et al., 2005; Johnson et al., 2006; Pope 2006; Stiegelmeier, 2006; Servidio, 2008).

The most economical and timely method for improving ground operations is to consider the future logistics requirements early in the design phase. A large portion of the future logistic effort is committed during this phase; therefore, the real challenge for designers is to wisely choose those aspects of the alternative designs that minimize logistic footprint during the vehicle operation. A design approach that places a premium on operability over performance could minimize or eliminate a number of turnaround functions such as those in the current Space Shuttle operations (McCleskey, 2005). Technology alone cannot assure high flight rates if the logistics footprint cannot be minimized. High-tech devices do not necessarily imply lower and faster maintenance (Rooney, 2003). Thus, the RLV design should consider a RLV that is “flexible, reliable and routinely operable” (Hartong and Rooney, 2004).

#### *Previous Ground Operations Simulation Models*

Since the beginning of the Space Shuttle program, many simulation studies which attempted to assess the logistics footprint of the RLV design have been conducted. Wilson et al. (1982) built a discrete event simulation model in Arena® software application called Shuttle Traffic Evaluation Model (STEM); this model was used as a tool to refine the flight scheduling

based on more accurate estimation of regeneration flights. Unfortunately, the utility of this program was limited by the lack of historical data (Johnson et al., 2008).

In 2002, Cates, Steele, Mollaghasemi, and Rabaldi presented another simulation model (created with Arena® software) in which ground processing activities data were fit into probability distributions. This NASA sponsored model, with approximately one thousand modules, was validated using historical data (Cates et al., 2002). Although NASA abandoned the plan of improving the regeneration time between flights before the model was finished, it was used in other scenarios such as mothballing a Shuttle Orbiter or closing Shuttle facilities (Johnson et al., 2008).

More recently, NASA used the previous simulation experiences to create a model called Manifest Assessment Simulation Tool (MAST) to assess the probability of completing a schedule of planned launches. This model considered orbiter maintenance, vehicle assembly and launch pad operations (Cates and Mollaghasemi, 2005). NASA used MAST to assess the probability of manifest completion before the Space Shuttle retirement in 2010 using Discovery, Atlantis and Endeavour orbiters (Cates and Mollaghasemi, 2005).

At his point, the models were only applicable to one type of vehicle, the Space Shuttle. They described how the launch vehicle affected the logistics footprint after the vehicle had been manufactured; however, the same NASA group of engineers built another model that could assess the logistics footprint before the RLV was manufactured. They wanted a model that enabled engineers to consider the logistics requirements of a new concept vehicle during the design phase. For this purpose, the model had to be flexible and sufficiently generic to allow the assessment of several different alternative designs. NASA developed the Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO) to estimate regeneration times

and flight rates. The generic model can be applied to multiple systems and provides a rapid feedback to the designer regarding the operational impact of the design decisions. Having worked on both specific and generic simulations of ground operations, NASA engineers compared the two methods and found that development time is longer and validation is more difficult in the case of the generic model. Once the model is built, though, the time required by the simulation study is shorter than that required in developing and analyzing the single system simulation (Steele et al, 2002).

The previous ground operations simulation models can be summarized as follows:

**Table 4. RLV simulation models**

<b>Model</b>	<b>Scope</b>	<b>Literature support</b>
Shuttle Traffic Evaluation Model (STEM)	Specific for Space Shuttle	Wilson <i>et al.</i> , 1982
Space Shuttle Modeling	Specific for Space Shuttle	Cates <i>et al.</i> , 2002
Manifest Assessment Simulation Tool (MAST)	Specific for Space Shuttle	Cates and Mollaghasemi, 2005
Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO)	Generic	Steele <i>et al.</i> , 2002

#### *MILEPOST Development*

The AFRL developed the Space Access Vehicles Mission and Operations Simulation (SAVMOS) to assess MSP concepts. SAVMOS is a computer simulation environment designed for modeling a MSP and its operations system. This model initially intended to study the performance of experimental aircraft like X-37/42 and conceptual hypersonic vehicles (Jacobs et al., 2005). Currently, it can assess preparation for flight, launch and space maneuvers, military operational missions, return to earth, and the preparation for the next cycle of performance (Jacobs et al., 2005).

SAVMOS considers the following systems: 1) Integrated Development & Operations Systems (IDOS), 2) Virtual Battlespace Management System (VBMS), 3) Space Operations Simulator (SOpsSIm), 4) Space Maneuver Vehicle Operations (SMVOps) and 5) Ground Operations (Jacobs et al., 2005).

By 2006, SAVMOS had not achieved an acceptable capability of modeling ground-based operations. The AFRL sponsored the Air Force Institute of Technology (AFIT) to develop a method for assessing the ground operations of the MSP. As a result, AFIT developed a model that studied post-flight recovery, maintenance, and pre-launch activities necessary for subsequent missions (Johnson et al., 2006). The model was called Maintenance, Integration, and Pad Simulation and Test (MILEPOST). Currently, MILEPOST is a part of SAVMOS (Johnson et al., 2008), providing it with logistics information necessary to evaluate candidate designs..

MILEPOST is a discrete-event simulation model that can evaluate candidate RLV recovery, maintenance, and pre-launch operations by simulating the regeneration time required for any specific vehicle design (Martindale, 2006; Pope, 2006; Stiegelmeier, 2006). The most important characteristic of MILEPOST is that the same simulation model can be used to assess logistic impact of different designs avoiding the need of building separate models for each specific design.

Using MILEPOST, designers can perform tradeoff studies on the impact of design characteristics on regeneration time and support personnel requirements. More than 50,000 distinct designs (or configurations) can be evaluated (by changing the number of motors, type of fuels, surface area of thermal protection systems, and more than 30 other design characteristics) without having to modify the model (Johnson et al., 2008). A Graphic Unit Interface (GUI) built

into MILEPOST allows the users to easily tailor any specific model (Pope, 2006; Stiegelmeier, 2006).

The MILEPOST model is similar to NASA's GEMFLO model in that both are generic models and can assess different designs. Additionally, they are built with the same software application and use the same approach to studying ground activities. They differ in that MILEPOST decomposes the ground operations into recovery, maintenance and prelaunch activities with much greater detail than GEMFLO (Johnson et al., 2008), because military missions for the future RLV are expected to be much more time sensitive. For example, whereas MAST was used to assess the probability of accomplishing 28 missions in almost 6 years by 3 orbiters (Cates and Mollaghasemi, 2005), military "rapid response" requirements are concerned with the probability of accomplishing missions in 48 hours (Rooney, 2003).

Even though the MILEPOST is generic, it still requires some basic assumptions. First, the model assumes the vehicle is unmanned. Second, it assumes the vehicle is a Hybrid Launch Vehicle, with a reusable first stage and expendable second stage. Finally, it assumes that the RLV launches vertically and lands horizontally (Johnson et al., 2006; Michalski & Johnson, 2007).

The problem with developing a generic model is that the vehicle does not yet exist; therefore, recovery, maintenance, and prelaunch operations sequences of the future RLV should be based on real systems that best approach the method by which the RLV will be operated and maintained (Steele et al., 2002). Thus, during the development of MILEPOST, the challenge for USAF simulation engineers was to select adequate aircraft and spacecraft with similar logistics requirements to the future RLV (Johnson et al., 2008).

Operation sequences set in the model are based on the Space Shuttle, Delta IV, Atlas IV, Minuteman III, Zenit 3SL, B-2 Bomber, and F-16 fighter. Undoubtedly, the Space Shuttle was chosen because it is the only RLV in operation. Atlas V and Delta IV were recently added to the U.S. ELVs fleet and have the most advanced technology. The Zenit 3SL was designed for quick prelaunch operations. The B-2 represents the most recent U.S. heavy load-capable aircraft; in addition to its complexity, its usage rate is similar to a RLV. Finally, the F-16 provides more knowledge on how quickly the RLV might be recovered for the next mission (Martindale, 2006; Johnson et al., 2006; Pope, 2006; Stiegelmeier, 2006).

Using these aircraft and spacecraft, the USAF engineers modeled MILEPOST ground operations which can be grouped in three sub-models: 1) Post landing operations, 2) Ground Maintenance operations and 3) Pre-launch operations. The three sub-models are discrete-event simulations developed in Arena®. While working simultaneously, the developers considered that the three sub-models must be compatible and use the same basic assumptions about the RLV. Additionally, two of the researches, Pope (2006) and Stiegelmeier (2006), worked together to developed a common Graphic Unit Interface (GUI) that allows the user to tailor design characteristics. After completion, the sub-models were assembled in the same simulation model.

### *Ground Maintenance Operations Modeling*

Pope (2006) constructed a sub-model that represents the logical sequence of expected maintenance tasks of a RLV and estimates the total maintenance duration. In order to construct the model, he identified the generic functions of RLV maintenance and compared them to several military aircraft, ELVs, and the Intercontinental Ballistic Missile (ICBM). He also

identified design drivers that affect type and duration of maintenance operations and included them in the model.

A Delphi panel of 19 experts ensured that Pope's model captured the best maintenance flow representing a reusable maintenance cycle. The members were chosen from different maintenance fields, such as B-2, IBCM, and Air Combat Command. They validated not only this sub-model but also the other two components of MILEPOST (Pope, 2006).

Pope completed his model for assessing RLV design characteristics and found that when two motors are used, increasing the efficiency in the thermal protection system (TPS) would have the greatest impact on the overall processing time. When more than two motors are used, the motor maintenance processes are more influential than TPS maintenance (Pope, 2006). Pope experimented with the model in a limited manner; only three configurations were studied. More experimentation with the model could present important findings.

Unfortunately, this model has limitations. First, the data used for simulating processing times of single activities was notional. This means that process times are based on educated guesses from experts instead of using parametric relationships. Second, the model was unconstrained by quantity or quality of resources; therefore, manpower requirements did not affect the results of the model. Finally, MILEPOST could only model one launch vehicle per run. For these reasons, he suggested that future studies should analyze the sensitivity of sortie production versus resource levels, and compare scheduled RLV missions to sortie production (Pope, 2006).

### *Prelaunch Operations Modeling*

Stiegelmeier's (2006) work focused on a very important aspect of vehicle regeneration: vehicle handling and servicing, also known as pre-launch operations. Stiegelmeier's model, the second MILEPOST sub-model, grouped pre-launch operations into payload integration, stage mating, vehicle transport and servicing.

The designed experiment did not yield an exact estimate of RLV regeneration time, but rather provided preliminary insights considering prelaunch operation options, such as second stage pre-integration and integration orientation (vertical vs. horizontal). As a conclusion of his study, he suggested some design strategies to minimize prelaunch operation time: pre-integration, integration off launch pad, horizontal orientation, and parallel propellant loading (Stiegelmeier, 2006).

In his suggestions for future research, he states that it would be worthwhile to use a computer simulation to analyze how different combinations of numbers of facilities, launch pads, first and second stages and other resources affect regeneration time and sortie rate. Since the performed experiment analyzed only one isolated processing decision, he recommended performing more experiments to study the impact of two or more processing decisions at the same time (Stiegelmeier, 2006).

### *Recovery Operations Modeling*

Martindale (2006) modeled the third sub-model of MILEPOST. For modeling the recovery activities, he studied mainly the Space Shuttle and F-16 recovery processes, with a logical emphasis on the orbiter due to the unique nature of future RLV. The comparison of F-16

and Space Shuttle Orbiter explained the need of adapting not only to the space system requirements, but also to the USAF goals in terms of rapid response.

As a result of his study, he found that automation (for example, for hazardous gas detection) and special handling requirements avoidance are key factors in reducing recovery process duration. He also found that, although sequences of post-flight activities between Space Shuttle and F-16 are similar, they vary greatly in complexity and duration. Martindale did not perform experiments to evaluate alternative design as part of his research (Martindale, 2006).

The development of the basic model can be summarized in the following table.

**Table 5. RLV simulation studies**

Model	Focus	Literature Support
Space Access Vehicles Mission and Operations Simulation (SAVMOS)	RLV preparation for flight, launch and space maneuvers, military operational missions, return to earth, and the preparation for the next cycle	Jacobs et al., 2005
Maintenance, Integration, and Pad Simulation and Test (MILEPOST)	Maintenance Operations	Pope, 2006
	Pre-launch Operations	Stiegelmeier, 2006
	Recovery Operations	Martindale, 2006

*Studies performed using MILEPOST*

*Process Time Refinement*

The following RLV studies followed two main objectives: 1) To improve the model fidelity and 2) To gain insight of ground operations using the recently built model. As Johnson et al. (2006) stated, a portion “of the following research steps will use the model to estimate the relationships between regeneration time and probable design configurations, using notional but plausible process times.”

Servidio’s research was related to the first objective: to improve model fidelity. Using Pope’s research suggestions, he attempted to improve the process time estimation by replacing

the educated notional approach with parametric relationships between maintenance factors and process times (Pope, 2006). Using USAF Reliability and Maintainability Information System (REMIS) data, Servidio established regression models for more than 60% of the maintenance activities; however, he suggested that further analysis is needed to establish parametric relationships for the rest of the activities where the regression models could not be built (Servidio, 2008).

### *Manpower Requirements and Organizational Assessment*

For the second objective of gaining insight into ground operations) many studies were performed (Johnson et al, 2006; Michalski, 2007; Michalski and Johnson, 2007; Michalski and Johnson 2008; Johnson and Jackson 2008, Johnson et al, 2008). Although the baseline MILEPOST model assumes unconstrained resources, it is evident that resource utilization plays a fundamental role in trade-off evaluations. Michalski (2007) estimated logistics manpower requirements for ground support of a RLV. She determined that the USAF B-2 Bomber Maintenance Group (MXG) and Logistics Readiness Squadron (LRS) provided the organizational structure that would best support regeneration operations for an RLV fleet. The requirements are expected to vary between approximately 1,200 and 2,400 personnel with a most likely value of 1,900 personnel for a 24-hour operation of six RLVs (Michalski and Johnson, 2007).

In addition, Michalski and Johnson conducted individual studies of the impact of specific characteristics in manpower requirements. For example, a Thermal Protection System similar to the Space Shuttle will increase maintenance support requirements by 30% of the established

baseline, and an Integrated Vehicle Health Management system could reduce the manpower requirements by 40% (Michalski and Johnson, 2007).

In 2008, Michalski and Johnson continued their studies about the military organizational structure that would best support the future RLV. They suggested two options: 1) a Logistics Readiness Squadron under the Mission Support Group or 2) a Maintenance Group that includes an RLV maintenance squadron for flight-line support, a Maintenance Squadron for backshop support, a Maintenance Operations Squadron, and a Munitions Squadron. They stated that more research is needed to estimate facilities, equipment, and materiel resources (Michalski and Johnson, 2008).

#### *Modeling Regeneration Time and Ground Support Manpower for a RLV*

Air Force simulation engineers performed several runs of the MILEPOST model to gain additional insight of design decisions regarding the manpower requirements increasing the number of decision factors. They considered a design in which 21 design decisions were fixed at pre-established values and performed a simulation experiment varying three ground operations alternatives: pre-integration, integration on pad and orientation (Johnson et al., 2008).

They established the initial manpower level by running the model with unconstrained resources to assess the maximum requirement for each technical specialty and deemed it as the manpower baseline. Next, they evaluated the design at different levels of the baseline. They found that increasing the manpower can only improve regeneration time up to a certain level, but additional time savings must come from vehicle design characteristics (Johnson et al., 2008).

One limitation of their work is that they did not consider the effect of successive, possibly overlapping, RLV missions on resource constraints, queuing behaviors or regeneration time.

They also suggested that new studies should focus on staffing, operations and support cost (Johnson et al., 2008).

#### *Other studies regarding future RLV support*

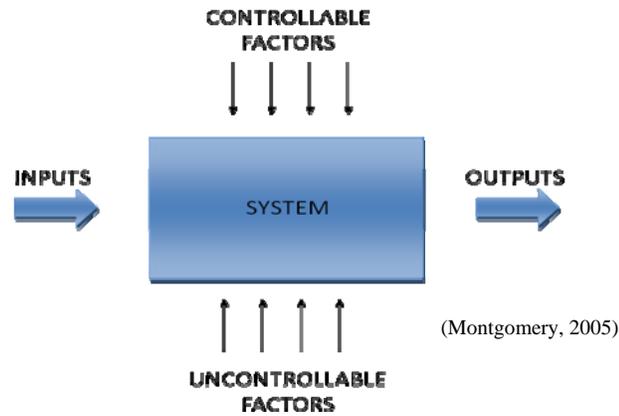
In 2008, Johnson and Jackson studied other aspects related to the life cycle ground support staffing for the RLV, assuming a six vehicles fleet, continuous operations and beddown at an existing Air Force Base (Johnson and Jackson, 2008). They found that 1) the maintenance group would range from 400 to 2400 personnel, depending on fleet size, health management systems, thermal protection technology, and vehicle size, and 2) the associated personnel cost would range from under \$80 million to \$160 million per year. They suggested that the USAF must decide whether it will proceed with the RLV program in the same contractor-conducted manner as was used for previous space launch systems or instead migrate its space systems ground support toward historical organic aircraft operations and sustainment processes (Johnson and Jackson, 2008).

#### **Methodology**

This study tailors the methodology in relation to each investigative question: 1) What are the effects of the design characteristics (design factors) in terms of turnaround time? 2) Which are the most relevant ones? 3) What combinations of these factors minimize the logistics footprint? Finally, 4) What are the effects of resource constraints in terms of manpower, ground support equipment, facilities and fleet size on the departure availability?

The aim of this research is to study the effects of the Reusable Launch Vehicle (RLV) design characteristics by means of a formal experiment that analyze all factors considered by the AFRL's MILEPOST discrete-event simulation model, which represents recovery, maintenance

and prelaunch operations of a RLV. Particular emphasis is placed on designing an appropriate experiment with the MILEPOST model. The study follows the general concept of any system or process model (see Figure 1): the inputs of the system are transformed into outputs, which depend on factors that both can and cannot be controlled by the operator or decision maker.



**Figure 1: General model of a process or system**

Since DOE allows “planning the experiment so that appropriate data that can be analyzed by statistical methods will be collected, resulting in valid and objective conclusions” (Montgomery 2005), it is necessary to plan the adequate inputs (RLV design characteristics) to the simulation model in order to collect data (RLV regeneration time) than can be analyzed by statistical methods in order to obtain valid conclusions. To address the investigative questions, we performed two experiments with different objectives: the first experiment relates to the investigative questions IQ1#, IQ#2 and IQ#3. The second experiment relates to IQ#4 and analyzes the effects resources such as manpower, ground support equipment, facilities and fleet size on the operational capability in terms of probability of accomplishing a given departure schedule.

## Experiment #1: Screening the effects of design characteristics

We first seek to identify the RLV design characteristics (factors) that have a significant effect on the time to recover the spacecraft for the next flight. The regeneration time is the response variable and represents all ground activities necessary for performing recovery, maintenance and prelaunch operations.

This experiment considers only one spacecraft. In addition to RLV design characteristics, limited resources (such as available manpower, ground support equipment and facilities) could also impact the response variable. These factors will remain fixed at established levels considered by MILEPOST as the “baseline.” Table 6 summarizes the factors used in the first experiment.

**Table 6. Experiment 1: Factors**

Factor	Type	Possible values	Meaning	Conditional
motors	categorical	0	repair engine on HLV	none
		1	modular	
total#ofmotors	discrete	3 to 5	Number of motors	none
Preintegration var	categorical	0	no preintegration	none
		1	preintegration	
Where integrate	categorical	0	off pad	none
		1	on pad	
Mx in int facility	categorical	0	Maintenance in int facility	if Where integrate == 0
		1	Maintenance in maintenance bay	If Where integrate <> 0
		1		
Int Orientation	categorical	0	horizontal	If Where integrate <> 0
		0	horizontal	
		1	vertical	if Where integrate == 0
Payload in int facility	categorical	0	Later on pad	if preintegration<>0 .and. where integrate<>0
		0		if preintegration==0 and where integrate==0
		1	Now in int facility	
Ordnance	categorical	0	no	none
		1	in int facility	if Where integrate == 0 (off pad)
		2	on pad	
		2	on pad	If where integrate ==1
erecting mechanism	categorical	0	built in	if Int Orientation== 0 (horizontal)
		1	separate	
		1	Separate	if Int Orientation== 1 (vertical)
Umbilicals	categorical	0	no umbilicals	none
		1	propellant connect	

		2	prop and electrical	
RP stages	categorical	0	no	none
		1	stage 1	
		2	stages 1 and 2	
Parallel RP var	categorical	0	default value	if RP stages == 0 .OR. RP stages==1
		0	serial	if RP stages == 2
		1	parallel	
Parallel cryo	categorical	0	Strict serial propellant loading	none
		1	Parallel stage and serial propellant loading	
		2	Parallel stage and propellant loading	
APU_automatic	categorical	0	no	none
		1	yes	
Purge_Inert_required	categorical	0	no	none
		1	yes	
Cooling_required	categorical	0	no	none
		1	yes	
Covers_required	categorical	0	no	none
		1	yes	
Taxi_Capable	categorical	0	no	none
		1	yes	
safety_downgrade_prob	continuous	0 to 100		none
batts_good_prob	continuous	0 to 100		none
engine_check_prob	continuous	0 to 100		if motors=0 (repair on HLV)
		99	DEFAULT	if motors=1 (modular)

The most desirable designed experiment is one that considers all factors and their interactions in the same experiment, called full factorial design. A full factorial design of the factors shown above would have almost 8 million possible combinations (also known as treatments). Each treatment corresponds to a single run of the simulation. Fortunately, as is shown in Table 3, not all possible combinations of the factors are feasible; the existence and values of some factors depend on the values of the others (i.e. they are conditional). As a result, from almost 8 million possible treatments, only 2.4 million are feasible. Unfortunately, this number still remains impractical; it is not computationally feasible to simulate such a huge number of treatments.

A logical approach when all feasible treatments cannot be performed is to consider all factors in an experiment which consider only the main effects on the design factors and some of the total interactions between them. In this case, the experiment is called a fractional factorial

design. The drawback to this type of design is that some interactions will not be considered or will be aliased with the main effects. Fractional factorial designs can be obtained using several statistical packages (JMP®, Design Expert, etc).

It is necessary to solve the problem of designing an experiment which includes only feasible treatments. To avoid this problem, we used super-variables, which represent two or more factors and whose levels represent only the feasible combinations of the variables. For example, “Uses RP super-variable” is a super-variable that has four levels, each one represents only the four feasible combinations of two components variables (RP stages, which has 3 levels: 0, 1 and 2; and Parallel RP var, which has 2 levels: 0 and 1). Note that although there are  $3 \times 2 = 6$  possible combinations, only 4 are feasible (see Table 7). The infeasible treatments in this table are indicated by gray shading.

**Table 7. Super-variables construction example**

“Uses RP super-variable” Super variable Levels	“RP stages” Variable Value	“Parallel RP var” Variable Value
1	0	0
	0	1
2	1	0
	1	1
3	2	0
4	2	1

We constructed three super-variables in this experiment; these account for the feasible combinations of the variables and are shown in Table 8.

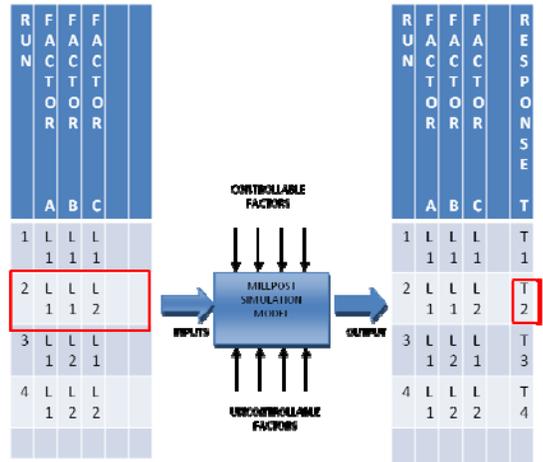
**Table 8. Super-variables used in the experiment 1**

<b>Super-variable</b>	<b>Levels</b>	<b>Variables included</b>
Motors super-variable	3	Motors (2 levels) Engine_check_prob (2 levels)
Uses RP super-variable	4	RP stages (3 levels) Parallel RP var (2 levels)
Integration super-variable	58	Preintegration var (2 levels) Where integrate (2 levels) Mx in int facility (2 levels) Int Orientation (2 levels) Erecting mechanism (2 levels) Payload in int facility (2 levels) Ordnance (3 levels)

The conditional factors in Table 6 are replaced using the super variable approach. Table 6 lists the factors used to design the experiment using JMP®. We generated a level III fractional factorial designed experiment which considered 11,136 treatments. The list was exported to a spreadsheet and used as input for the simulation model MILEPOST. Each treatment was replicated 5 times. As a result, 55,680 RLV launches were simulated, and their associated regeneration time analyzed. The results of the simulation model (regeneration time for each treatment) were written to the same spreadsheet. The procedure is depicted in Figure 2.

**Table 9. Factors used to create the DOE table using JMP®**

<b>Variable name</b>	<b>Type</b>	<b>Levels</b>
Motors super-variable	categorical	3
total#ofmotors	discrete	3
umbilicals	categorical	3
Parallel cryo	categorical	3
APU_automatic	categorical	2
Purge_inert_required	categorical	2
Cooling_required	categorical	2
Covers_required	categorical	2
Taxi_Capable	categorical	2
safety_downgrade_prob	continuous	2
batts_good_prob	continuous	2
Uses RP mixture	categorical	4
Integration mixture	categorical	58



**Figure 2. Experiment 1 procedure**

### Findings of experiment 1

Once the regeneration time for each treatment was obtained using the MILEPOST model, an analysis of variance (ANOVA) of only main effects was performed. Considering the mean square error for each factor in the model and the total mean square error, an  $F_0$  statistic is generated to identify the significant effects. When considering only main effects, some were found not to be statistically significant: engine check success probability ( $p = 0.7676$ ), Rocket Propellant parallel loading ( $p = 0.1639$ ), Taxiing Capability ( $p = 0.8312$ ), the probability of being safe to proceed with total downgrade ( $p = 0.2424$ ) and batteries check success probability ( $p = 0.660$ ). The complete ANOVA obtained from JMP® is shown in Appendix 1.

We constructed a first regression model using the regeneration time as the response variable and the design characteristics as factors. The adjusted  $R^2$  is 0.981. Of all interactions analyzed, only two significant interactions were found: “motors” and “number of motors” ( $F = 21696.07$ ), and the “preintegration” and “where to integrate” ( $F = 51.4138$ ). The results of the regression model are included in Appendix 2. From the scaled estimates of the regression coefficients, we note the following findings:

- There is an important practical difference between the type of motors (modular or not) the RLV uses. When motors are modular, the increase in the regeneration time is about 9.5 hours. This increase in time may be related to the activities of removing and re-installing the engines. In addition, we must add 10.22 hours to the mean regeneration time for adding a fourth motor to the RLV and to 10.41 hours for adding a fifth one.
- Propellant umbilical connections represent an increase of 0.65 hours to the regeneration time when compared to a design in which there is no need for separate umbilical connections; adding propellant and electrical increases the regeneration time 1.5 hours.
- Adding rocket propellant (RP) to stage 1 represents an increase of 1.08 hours to the regeneration time. If we also include stage 2, the total regeneration time is increased to 1.82 hours.
- There is no practical difference in the impact on the regeneration time between a taxiing capable and a non taxiing capable design (only 0.04 hours).
- There is no practical difference in the impact on the regeneration time between integrating the payload in the integration facility versus on pad (only 0.16 hours).
- When the auxiliary power unit shut down is automatic, more time is required (0.32 hours).
- When purge inert is required, the regeneration time increases by 1 hour.
- If cooling is required, the regeneration time increases 0.84 hours.
- Pre-integration of payload and stage 2 prior to joining with stage 1 reduces the regeneration time 3.65 hours.

- Integrating on pad represents an increase of 0.68 hours compared to integrating off pad.
- Vertical orientation is slower than horizontal orientation by 3.57 hours.
- If the erecting mechanism is separate, the regeneration time increases 0.52 hours.
- Adding ordnance to the regeneration activities represents an increase of 6.53 hours; there is no practical significance whether the related activities take place on pad or in the integration facility.
- Integrating the payload in the integration facility reduces the time by 1.36 hours.

We checked the validity of the model (adjusted  $R^2 = 0.981$ ). A plot of the Actual Regeneration Time versus the predicted Regeneration Time is shown in Appendix 2. The graph of response residuals versus predicted shows that the variance is higher for lower values of the response (Appendix 2). The studentized residuals were also analyzed. Visual inspection of the curve may suggest a normal distribution of residuals; however, statistical analysis does not. The KSL test is 0.013521, which implies that the residuals are not normally distributed. Changing interval widths shows a normal distribution that indicated a robust deviation from normality. This issue is common in software packages when dealing with high numbers of observations. There is no particular observation that may influence the model in a significant way. The maximum value of Cook's Distance is only 0.0007 (much less than maximum acceptance value of 0.05)

Although all the factors included in the model are statistically significant ( $p < 0.05$ ), we must highlight that some of them have little impact on the regeneration time. We constructed a second model, which uses a reduced number of factors, including only those whose impact on the

regeneration time is greater than 0.4 hours. This second regression yields an adjusted  $R^2 = 0.976$ . The results are shown in Appendix 3. The model is simpler than the first one since it uses fewer factors. Table 10 summarizes the factors considered in each of the models:

**Table 10. Comparison of two regression models**

Factors	Regression model 1 -all statistically significant factors ( $p < 0.05$ ) Radj=0.981	Regression model 2 -only practically significant factors ( $B_i > 0.4$ hours) Radj=0.976
motors	Yes	Yes
engine_check_prob	No	No
total#ofmotors	Yes	Yes
umbilicals	Yes	Yes
RP stages	Yes	Yes
Parallel RP var	No	No
Parallel cryo	No	No
Taxi_Capable	Yes	No
APU_automatic	Yes	No
Purge_Inert_required	Yes	Yes
Cooling_required	Yes	Yes
Covers_required	Yes	Yes
Preintegration var	Yes	Yes
Where integrate	Yes	No
Mx in int facility	Yes	No
Int Orientation	Yes	Yes
Ordnance	Yes	Yes
erecting mechanism	Yes	Yes
Payload in int facility	Yes	Yes
safety_downgrade_prob	No	No
Batts_good_prob	No	No
motors* total#ofmotors	Yes	Yes
Preintegration var* Where integrate	Yes	No

We next identified the RLV design that minimizes the logistics footprint in terms of regeneration time (best configuration) and the RLV design that requires the longest regeneration time (worst configuration). These results are summarized in Table 11. After 50 replications we found the mean regeneration time and variance for the best configuration (mean = 51.32 hours, variance = 3.66 hours<sup>2</sup>) and the worst configuration (mean = 103.54 hours, variance = 1.83 hours<sup>2</sup>). A t-test showed that the means are significantly different ( $t = 157.54, p < 0.001$ )

**Table 11. Best and Worst RLV designs**

FACTOR	Best Configuration Mean Reg time 51.32 hs CI : (50.78, 51.86)	Worst Configuration Mean Reg time: 103.54 hs CI : (103.25, 103.92)
Motors	0 (repair motor on RLV)	1 (Modular motor design)
engine_check_prob	99%	99%
total#ofmotors	3	5
Umbilicals	0 (simple)	2 (complex)
RP stages	0 (NO)	2 (RP in stage 1 and stage 2)
Parallel RP var (RP loading of the stage 1 and 2 at the same time ?)		1 (NO –serial loading)
Parallel cryo	1 (YES)	0 (NO)
Taxi_Capable	0 (NO)	1 (YES)
APU_automatic	0 (NO)	1 (YES)
Externalstores_capable	0 (NO)	1 (YES)
Externalstores_yes	0(NO)	1 (YES)
Purge_Inert_required	0(NO)	1(YES)
Cooling_required	0(NO)	1(YES)
Covers_required	0(NO)	1(YES)
Preintegration var (integration of payload and stage 2 before joining to stage 1)	1(YES)	0(NO)
Where integrate	0 (OFF PAD)	1 (ON PAD)
Mx in int facility (where is integrated ?)	1 (Maintenance Bay)	
Int Orientation	0 (Horizontal)	1 (Vertical)
Ordnance	0 (NO)	1 (YES ON Pad)
erecting mechanism	0 (Built in)	1 (NO)
Payload in int facility	0 (NO)	
safety_downgrade_prob	99%	80%
Batts_good_prob	99%	80%

This section explained the experiment design, methodology, analysis techniques and results for the first experiment. The next section includes the same information for the second experiment.

**Experiment #2: Analysis of the effects of resources on departure availability**

The second experiment analyzes the effects that resources and fleet size have on departure availability for the best and worst RLV designs (from the first experiment), given a departure schedule. The objective is to maximize the probability of accomplishing that schedule. This probability is calculated as a percentage of accomplished departures divided by the number of planned departures.

The response variable is called departure availability, abbreviated “Dep\_Av.” The decision variables are fleet size and the percentage of the baseline resources. These resources are divided into three categories: manpower, facilities and ground support equipment. These factors vary from 100% to 700% of the baseline (the established number of resources necessary to perform all RLV ground activities considered by MILEPOST). Table 12 shows the factors used in the experiment. Each one of these factors modifies the available resources in the simulation model; Table 1 in Appendix 4 details how the resources are grouped.

**Table 12. Factors used in the experiment 2**

<b>Factor</b>	<b>Type</b>	<b>Range</b>
fleet size	Discrete	1 to 7
Manpower factor	Continuous	100% to 700%
GSE_factor	Continuous	100% to 700%
Facility_factor	Continuous	100% to 300%

The experiment consists of simulating the launch of one spacecraft to a mission every 24 hours during a period of 100 days of continuous operations. We assessed the departure availability for both the best and worst RLV design in terms of regeneration time, which was already established in experiment 1. We ran the MILEPOST model using a full factorial design in which all possible combinations of the decision variables are evaluated. The simulation records the ratio between launches and planned departures. There were a total of  $7 \times 7 \times 7 \times 3 = 1029$  treatments for each configuration considered in this experiment.

### **Findings of experiment #2**

We performed an Analysis of Variance (ANOVA), presented in Table 13, to assess the factors and found that the GSE factor was not significant under the given conditions.

**Table 13. Parameter Estimates of experiment 2**

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-0.174708	0.013224	-13.21	<.0001
Best Config	0.3116229	0.005914	52.69	0.0000
Fleet size	0.0586795	0.001478	39.69	<.0001
Facilityfactor	0.0016652	3.622e-5	45.98	<.0001
Manpower	7.2036e-5	1.478e-5	4.87	<.0001
GSEfactor	-4.009e-7	1.478e-5	-0.03	0.9784

The results are presented in six different graphs and tables in which the Dep\_Av is shown as a function of fleet size and manpower. We considered six scenarios which are shown in Table 14.

**Table 14. Scenarios in experiment 2**

Scenario	Configuration	Facilities
1	Best (shortest regeneration time)	100 %
2	Best (shortest regeneration time)	200 %
3	Best (shortest regeneration time)	300 %
4	Worst (longest regeneration time)	100 %
5	Worst (longest regeneration time)	200 %
6	Worst (longest regeneration time)	300 %

Scenario 1: Best Configuration and 1 facility

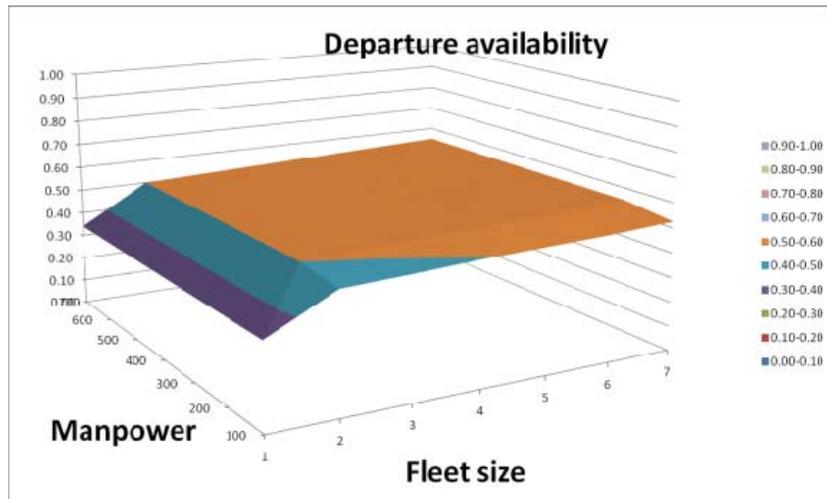


Figure 3. Departure Availability- Scenario 1

Scenario 2: Best configuration and 2 facilities

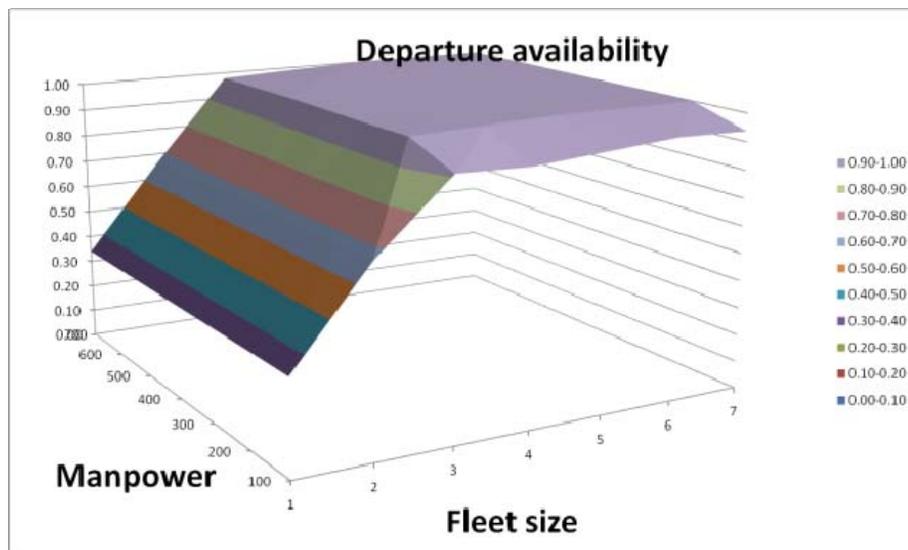


Figure 4. Departure Availability- Scenario 2

Scenario 3: Best configuration and 3 facilities

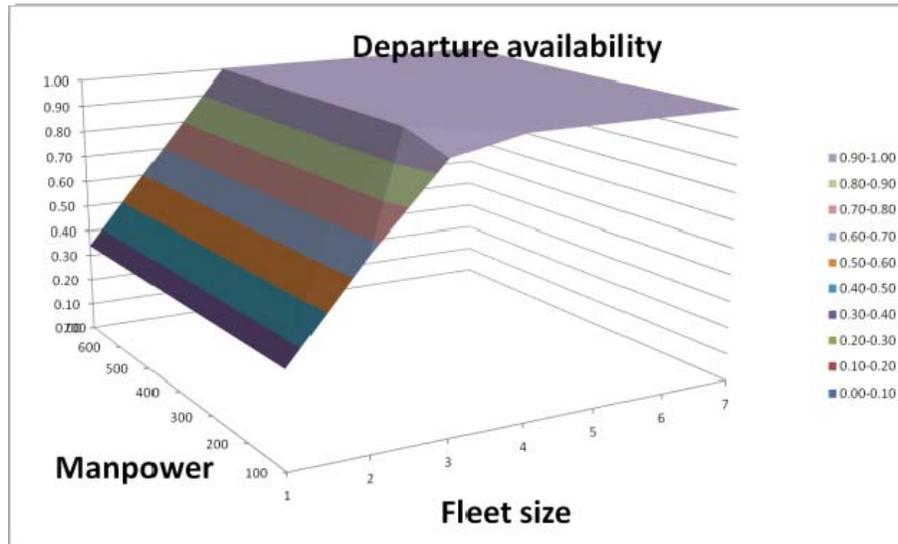


Figure 5. Departure Availability- Scenario 3

Scenario 4: Worst configuration and 1 facility

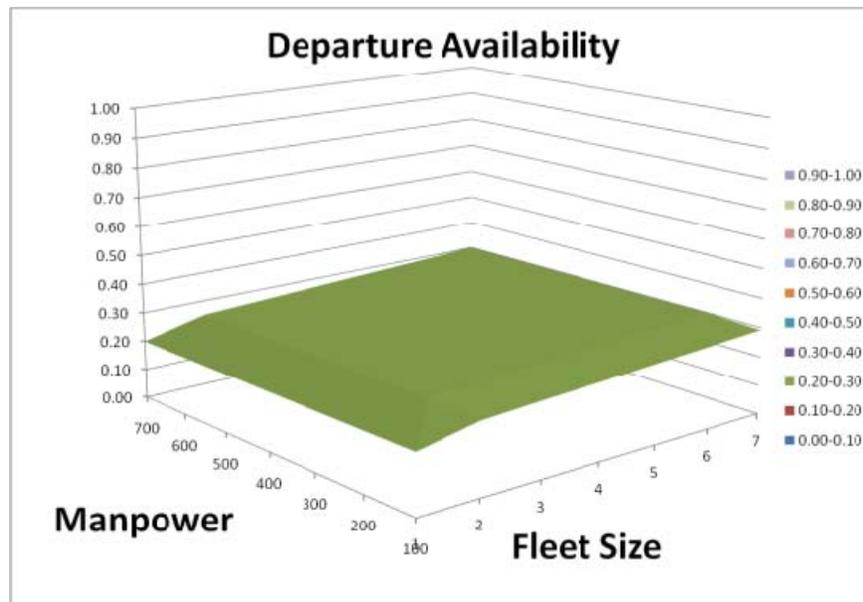


Figure 6. Departure Availability- Scenario 4

Scenario 5: Worst configuration and 2 facilities

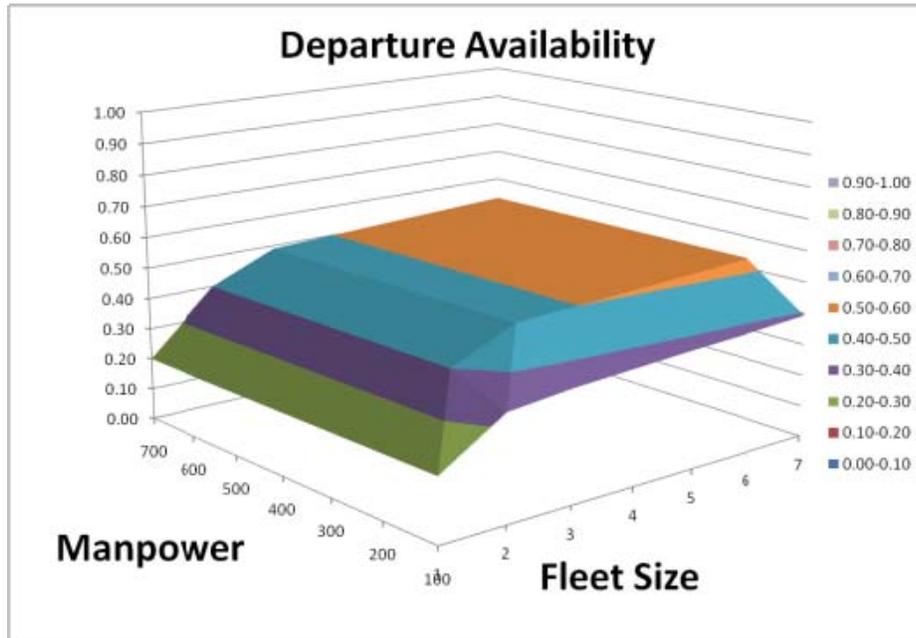


Figure 7. Departure Availability- Scenario 5

Scenario 6: Worst configuration and 3 facilities

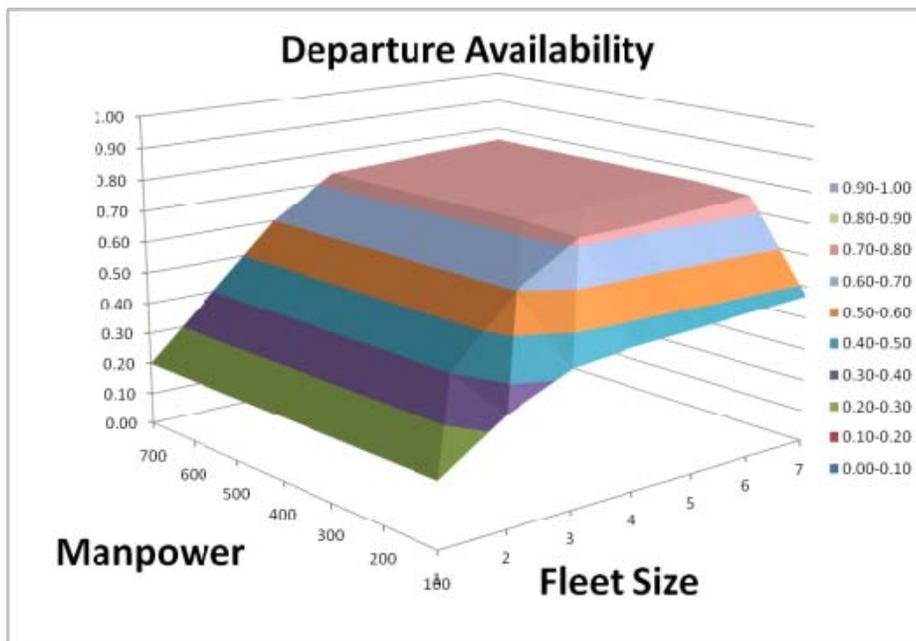


Figure 7. Departure Availability- Scenario 5

When analyzing these results, it is very important to consider that when one resource becomes the constraint, increasing other resources does not necessarily improve the output. Our findings can be summarized as follows:

- For one single facility and the best design configuration, increasing the fleet size from 1 to 7 improves the departure availability from 34% to 55%.
- For two and three facilities and the best design configuration, increasing the fleet size from 1 to 7 improves the departure availability from 34% to 100%.
- For one single facility and the worst configuration, increasing the fleet size from 1 to 7, improves the departure availability from 20% to 30%.
- For two facilities and the worst configuration, increasing the fleet size from 1 to 7, improves the departure availability from 20% to 51%.
- For three facilities and the worst configuration, increasing the fleet size from 1 to 7, improves the departure availability from 20% to 71%.
- When dealing with one single facility, increasing manpower further than 200% produces no availability improvement.
- When dealing with two single facilities, increasing manpower further than 300% produces no availability improvement.
- There is a significant difference in departure availability between the worst and best configuration. In the less favorable case, the difference is

14% and in the more favorable case, departure availability can be increase from 53% to 100% when selecting the best RLV design configuration

## **Conclusions**

We assessed the effects of the most relevant characteristics on turnaround time for a RLV. We found that the use of super variables is very convenient to avoid infeasible treatments in a relatively simple and computationally inexpensive manner. Analysis showed that the type of motor (modular or not) and the number of motors have the most important impacts on regeneration time. We also found that “preintegration” of the payload and stage 2 before joining to stage 1 save some time, and that horizontal orientation is faster than vertical. Also, integration of the payload in an integration facility can reduce the total time. In contrast, the need for ordnance, umbilicals, covers, purging or cooling increases the regeneration time.

There are several factors that have no relevant impact on the regeneration time: engine probability check, the method by which Rocket Propellant fuels and cryogenic propellant are loaded, taxi capability, auxiliary power unit automatic shutdown, the type of erecting mechanism, the place where ordnance takes place, probability of being safe with total downgrade and the probability that the batteries are good.

The second experiment showed that by selecting a good design, the departure availability can increase significantly. We also found that the increase of manpower does not improve the departure availability unless the facility resources are expanded. We found that ground support equipment has no significant effect, because the constraint is

the facilities resources (launch pad, integration facility, vehicle transporter and maintenance bay).

Among the limitations of the study, we have to highlight that a different grouping of resources could yield different results regarding departure availability. Only one of the facilities resources is the bottleneck; therefore, increasing that particular resource should increase availability. Treating each resource in a separate way, increases the magnitude of the problem very rapidly, and a full factorial design would be infeasible ( $3 * 10^{26}$ ). Future studies could consider wider ranges of resources and also different departure schedules.

## **IV. Conclusions and Recommendations**

### **Conclusions**

In addition to the conclusions stated in the journal article, it can be highlighted that the procedure of using super-variables to avoid unfeasible combinations facilitated the design of the experiment. The use of Excel® spreadsheets facilitates the automatic input for Arena®, making this data entry feasible. Otherwise, it could be tedious (or perhaps even impossible) to perform the simulation.

When identifying the relevant RLV design characteristics, the results obtained are satisfactory, since they reduce the initial number of factors to only a few that have an important impact on the regeneration time. The second experiment shows how important it is to refine the design characteristics, since the final configuration has a very high impact on the departure availability.

### **Limitations of the study**

The recommended design strategy is limited to the capabilities of AFRL's MILEPOST discrete event simulation model. This implies that other RLV design characteristics could affect the regeneration time, but these were not considered in the model and therefore are not in this study.

Another important issue is that the RLV does not exist yet, since it is a concept vehicle, and the analysis is relying on analogies of existing spacecraft and aircraft which may not accurately represent the future RLV.

The results of departure availability could depend in the manner in which resources are grouped. Only one of the facilities resources is the bottleneck, so with an increase in that particular resource, availability should increase. Treating each resource in a separate way increases the magnitude of the problem very rapidly, and a full factorial design would be computationally unfeasible ( $3 * 10^{26}$  combinations). Future studies could consider wider ranges of resources.

The study could have used different schedules and would produce different results. The shorter the time between planned mission, the lower the departure availability.

### **Future Research**

Future studies could focus more on working with resources and refining the way in which resources are grouped. They could also make the time between missions variable and reevaluate the departure availability.

It is also very important to upgrade the model as designers refine the design of the concept vehicle. Not only do the activity times need to be updated, but also new features might need to be considered by the simulation model.

**Table 1. ANOVA mains effects**

<b>Source</b>	<b>Sum of Squares</b>	<b>F Ratio</b>	<b>Prob &gt; F</b>
motors	1600866.2	393648.1	0.0000
engine_check_prob	0.35526338	0.0874	0.7676
total#ofmotors	3523257.9	433179.2	0.0000
umbilicals	27496.8	3380.686	0.0000
RP stages	19188.5	2359.191	0.0000
Parallel RP var	7.9	1.9375	0.1639
Parallel cryo	53.6	6.5878	0.0014
Taxi_Capable	0.18467893	0.0454	0.8312
APU_automatic	1965.0	483.1923	<.0001
Purge_Inert_required	11702.1	2877.517	0.0000
Cooling_required	8915.6	2192.321	0.0000
Covers_required	15882.2	3905.374	0.0000
Preintegration var	119397.9	29359.59	0.0000
Where integrate	1658.0	407.7083	<.0001
Mx in int facility	751.9	184.8925	<.0001
Int Orientation	87297.1	21466.08	0.0000
Ordnance	499494.7	61412.11	0.0000
erecting mechanism	1619.9	398.3366	<.0001
Payload in int facility	13140.7	3231.265	0.0000
safety_downgrade_prob	5.6	1.3665	0.2424
batts_prob	0.78693185	0.1935	0.6600

## Regression Model: Regeneration Time of a RLV (full model)

### Summary of Fit

RSquare	0.981385
Rsquare Adj	0.981377
Root Mean Square Error	1.511561
Mean of Response	75.33539
Observations (or Sum Wgts)	55680

### Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	23	6704083.0	291482	127573.4	
Error	55656	127163.8	2.284817		
C. Total	55679	6831246.8			0.0000

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	67.740918	0.020042	3379.9	0.0000
motors[0]	-4.799858	0.011773	-407.7	0.0000
total#ofmotors[4-3]	10.227779	0.016644	614.52	0.0000
total#ofmotors[5-4]	10.410662	0.016654	625.13	0.0000
umbilicals[0]	-0.790655	0.009062	-87.25	0.0000
umbilicals[1]	-0.155382	0.00906	-17.15	<.0001
RP stages[0]	-0.911293	0.010016	-90.98	0.0000
RP stages[1]	0.1723503	0.010016	17.21	<.0001
Taxi_Capable[0]	-0.020312	0.006407	-3.17	0.0015
APU_automatic[0]	0.1600005	0.006408	24.97	<.0001
Purge_Inert_required[0]	-0.504311	0.00641	-78.68	0.0000
Cooling_required[0]	-0.418989	0.006407	-65.40	0.0000
Covers_required[0]	-0.547478	0.006407	-85.45	0.0000
Preintegration var[0]	1.8277663	0.010922	167.34	0.0000
Where integrate[0]	-0.342413	0.012928	-26.49	<.0001
Mx in int facility[0]	0.0878672	0.007486	11.74	<.0001
Int Orientation[0]	-1.786737	0.009237	-193.4	0.0000
Ordnance[0]	-4.352862	0.009383	-463.9	0.0000
Ordnance[1]	2.1810876	0.010073	216.52	0.0000
erecting mechanism[0]	-0.261811	0.009075	-28.85	<.0001
Payload in int facility[0]	0.6823108	0.009377	72.76	0.0000
motors[0]*total#ofmotors[4-3]	-1.839742	0.016666	-110.4	0.0000
motors[0]*total#ofmotors[5-4]	-1.63142	0.016676	-97.83	0.0000
Preintegration var[0]*Where integrate[0]	-0.077537	0.010814	-7.17	<.0001

### Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
motors	1	1	379809.2	166231.8	0.0000
total#ofmotors	2	2	3514230.7	769039.9	0.0000
umbilicals	2	2	28649.4	6269.521	0.0000
RP stages	2	2	25270.5	5530.102	0.0000
Taxi_Capable	1	1	23.0	10.0519	0.0015
APU_automatic	1	1	1424.5	623.4778	<.0001
Purge_Inert_required	1	1	14144.2	6190.499	0.0000
Cooling_required	1	1	9772.5	4277.149	0.0000
Covers_required	1	1	16684.5	7302.316	0.0000
Preintegration var	1	1	63981.1	28002.72	0.0000
Where integrate	1	1	1602.8	701.4976	<.0001
Mx in int facility	1	1	314.8	137.7825	<.0001

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Int Orientation	1	1	85492.7	37417.74	0.0000
Ordnance	2	2	492287.8	107730.2	0.0000
erecting mechanism	1	1	1901.8	832.3850	<.0001
Payload in int facility	1	1	12097.2	5294.602	0.0000
motors*total#ofmotors	2	2	99143.1	21696.07	0.0000
Preintegration var*Where integrate	1	1	117.5	51.4138	<.0001

## Scaled Estimates

Nominal factors expanded to all levels

Term	Scaled Estimate	Std Error	t Ratio	Prob> t
Intercept	67.740918	0.020042	3379.91	0.0000
motors[0]	-4.799858	0.011773	-407.72	0.0000
motors[1]	4.7998584	0.011773	407.72	0.0000
total#ofmotors[4-3]	10.227779	0.016644	614.52	0.0000
total#ofmotors[5-4]	10.410662	0.016654	625.13	0.0000
umbilicals[0]	-0.790655	0.009062	-87.25	0.0000
umbilicals[1]	-0.155382	0.00906	-17.15	<.0001
umbilicals[2]	0.9460366	0.00906	104.42	0.0000
RP stages[0]	-0.911293	0.010016	-90.98	0.0000
RP stages[1]	0.1723503	0.010016	17.21	<.0001
RP stages[2]	0.7389431	0.008542	86.51	0.0000
Taxi_Capable[0]	-0.020312	0.006407	-3.17	0.0015
Taxi_Capable[1]	0.0203118	0.006407	3.17	0.0015
APU_automatic[0]	0.1600005	0.006408	24.97	<.0001
APU_automatic[1]	-0.16	0.006408	-24.97	<.0001
Purge_Inert_required[0]	-0.504311	0.00641	-78.68	0.0000
Purge_Inert_required[1]	0.5043112	0.00641	78.68	0.0000
Cooling_required[0]	-0.418989	0.006407	-65.40	0.0000
Cooling_required[1]	0.4189891	0.006407	65.40	0.0000
Covers_required[0]	-0.547478	0.006407	-85.45	0.0000
Covers_required[1]	0.5474778	0.006407	85.45	0.0000
Preintegration var[0]	1.8277663	0.010922	167.34	0.0000
Preintegration var[1]	-1.827766	0.010922	-167.34	0.0000
Where integrate[0]	-0.342413	0.012928	-26.49	<.0001
Where integrate[1]	0.3424131	0.012928	26.49	<.0001
Mx in int facility[0]	0.0878672	0.007486	11.74	<.0001
Mx in int facility[1]	-0.087867	0.007486	-11.74	<.0001
Int Orientation[0]	-1.786737	0.009237	-193.44	0.0000
Int Orientation[1]	1.7867368	0.009237	193.44	0.0000
Ordnance[0]	-4.352862	0.009383	-463.91	0.0000
Ordnance[1]	2.1810876	0.010073	216.52	0.0000
Ordnance[2]	2.1717743	0.009784	221.98	0.0000
erecting mechanism[0]	-0.261811	0.009075	-28.85	<.0001
erecting mechanism[1]	0.2618107	0.009075	28.85	<.0001
Payload in int facility[0]	0.6823108	0.009377	72.76	0.0000
Payload in int facility[1]	-0.682311	0.009377	-72.76	0.0000
motors[0]*total#ofmotors[4-3]	-1.839742	0.016666	-110.39	0.0000
motors[0]*total#ofmotors[5-4]	-1.63142	0.016676	-97.83	0.0000
motors[1]*total#ofmotors[4-3]	1.8397418	0.016666	110.39	0.0000
motors[1]*total#ofmotors[5-4]	1.6314196	0.016676	97.83	0.0000
Preintegration var[0]*Where integrate[0]	-0.077537	0.010814	-7.17	<.0001
Preintegration var[0]*Where integrate[1]	0.0775374	0.010814	7.17	<.0001
Preintegration var[1]*Where integrate[0]	0.0775374	0.010814	7.17	<.0001
Preintegration var[1]*Where integrate[1]	-0.077537	0.010814	-7.17	<.0001

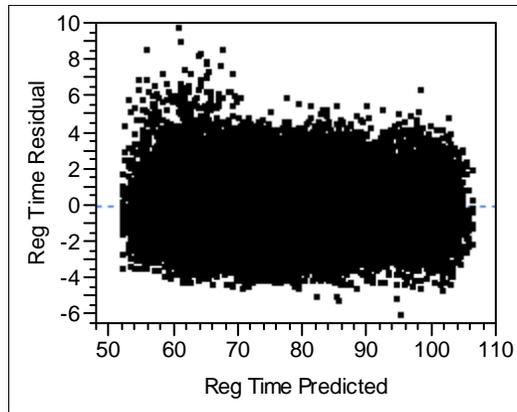


Figure 1. Residuals plot

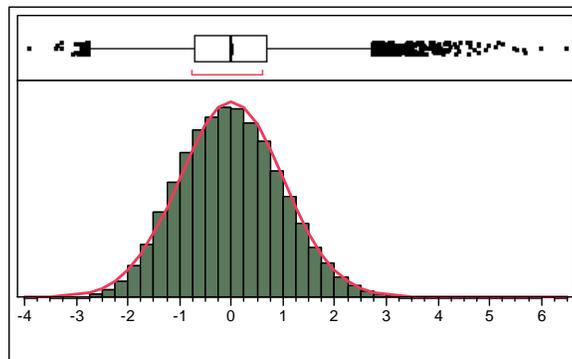


Figure 2. Residuals distribution

## Regression Model: Regeneration Time of a RLV (simple model)

### Summary of Fit

RSquare	0.976099
RSquare Adj	0.976093
Root Mean Square Error	1.712652
Mean of Response	75.33539
Observations (or Sum Wgts)	55680

### Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	15	6667974.5	444532	151552.9	
Error	55664	163272.4	2.933177		
C. Total	55679	6831246.8			0.0000

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	67.574693	0.015038	4493.6	0.0000
motors[0]	-4.817394	0.01333	-361.4	0.0000
total#ofmotors[4-3]	10.218172	0.018856	541.91	0.0000
total#ofmotors[5-4]	10.412555	0.018868	551.88	0.0000
RP stages[0]	-0.912429	0.011349	-80.40	0.0000
RP stages[1]	0.1730598	0.011348	15.25	<.0001
Purge_Inert_required[0]	-0.503893	0.007262	-69.38	0.0000
Cooling_required[0]	-0.418997	0.007259	-57.72	0.0000
Covers_required[0]	-0.547155	0.007259	-75.38	0.0000
Preintegration var[0]	1.7007026	0.008528	199.44	0.0000
Int Orientation[0]	-1.88014	0.008196	-229.4	0.0000
Ordnance[0]	-4.413238	0.010292	-428.8	0.0000
Ordnance[1]	2.1001177	0.010983	191.22	0.0000
Payload in int facility[0]	0.6960745	0.010214	68.15	0.0000
motors[0]*total#ofmotors[4-3]	-1.8086	0.018866	-95.86	0.0000
motors[0]*total#ofmotors[5-4]	-1.642184	0.01888	-86.98	0.0000

### Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
motors	1	1	383103.4	130610.4	0.0000
total#ofmotors	2	2	3512516.3	598756.3	0.0000
RP stages	2	2	25318.4	4315.865	0.0000
Purge_Inert_required	1	1	14120.8	4814.155	0.0000
Cooling_required	1	1	9772.9	3331.855	0.0000
Covers_required	1	1	16664.8	5681.490	0.0000
Preintegration var	1	1	116667.6	39775.16	0.0000
Int Orientation	1	1	154369.2	52628.68	0.0000
Ordnance	2	2	544602.3	92834.89	0.0000
Payload in int facility	1	1	13622.7	4644.345	0.0000
motors*total#ofmotors	2	2	98144.5	16730.06	0.0000

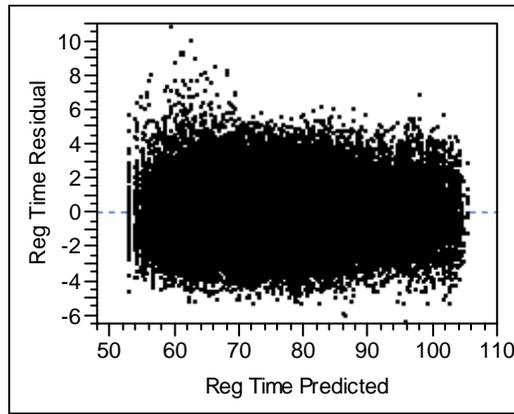


Figure 1. Residuals plot

**Table 1. Resources Grouping**

<b>Order</b>	<b>Name</b>	<b>Baseline Quantity</b>	<b>Type of resource</b>
1	launch pad	1	Facility
2	integration facility	1	Facility
3	vehicle transporter	1	Facility
4	Maintenance Bay	1	Facility
5	Stage1	1	Facility
6	RJD and Drag Chute GSE	1	GSE
7	Fore Safety Assessment GSE	1	GSE
8	Purge GSE	1	GSE
9	Coolant GSE	1	GSE
10	Protective_cover_GSE	1	GSE
11	Tow_Tug	1	GSE
12	MX_GSE_safety_downgrade	1	GSE
13	Dispersal_GSE_HazGas	1	GSE
14	Aft Safety Assessment GSE	1	GSE
15	ExternalStoreSeparateGSE	1	GSE
16	APU GSE	1	GSE
17	GroundCrewAutoAssessGSE	1	GSE
18	LOX_GSE	1	GSE
19	Crew Chief	7	Manpower
20	Backshop Avionics	3	Manpower
21	Wheel and Tire	3	Manpower
22	On Board Diagnostics	2	Manpower
23	Flightline Avionics	4	Manpower
24	Backshop Propulsion	6	Manpower
25	Flightline Propulsion	4	Manpower
26	Egress	3	Manpower
27	Fuel Cell	5	Manpower
28	Backshop Hydraulics	3	Manpower
29	Flightline Hydraulics	3	Manpower
30	Backshop E and E	2	Manpower
31	Flightline E and E	3	Manpower
32	Structures	12	Manpower
33	Fuels	3	Manpower
34	Munitions	7	Manpower
35	Backshop Armament	5	Manpower
36	Flightline Armament	7	Manpower
37	RLV	1	Fleet

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### **Vita**

Lt. Col. Carlos Alberto Molina graduated as an officer from the Argentine Air Force Academy in 1988. He is an aeronautical engineer graduated from the Argentine Air Force Institute of Technology.

He had several assignments in aircraft maintenance squadrons. In 2004 he graduated as Staff Officer at the Argentine Air Force War College. He was assigned the Materiel Command Staff until he entered the Graduate School of Engineering and Management, Air Force of Technology in August 2007. Upon graduation he will be assigned to the Materiel Command Staff in Buenos Aires, Argentina.

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<b>14. ABSTRACT</b> In last few years the Air Force Research Laboratory sponsored several research projects on Reusable Launch Vehicles (RLV) whose design, operation, and logistics requirements are intended to be much simpler than the Space Shuttle. Previous researchers developed a model that simulated the post-landing, ground maintenance and prelaunch operations of a RLV in order to evaluate how its design parameters affect the logistics operations. However, the next step was to investigate the effects and interactions of all the factors used in the existing simulation model in a single experiment that deals with the huge number of possible design characteristics' combinations discovered in previous studies and varying resources like manpower, ground support equipment and facilities. The goal of this research is to recommend to the AFRL a preferred design strategy that could minimize the resource requirements in terms of equipment and manpower as well as turnaround time of logistics operations.					
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U	U	U	UU	88	Alan W. Johnson, PhD, ENS (937) 255-3636, ext 4703 (Alan.Johnson@afit.edu)