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Modeling Regeneration Time and Ground Support Manpower for a Reusable Launch Vehicle

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The military is pursuing a low-cost, responsive reusable launch vehicle that can rapidly place payloads in orbit in response to national defense requirements. The reusable launch vehicle is currently in the early stages of its design phase, when it is critical to assess design alternatives in terms of their operational capabilities as well as their life cycle support requirements. The U.S. Air Force Research Laboratory developed the space access vehicles mission and operations simulation (SAVMOS) model suite to assist in evaluating the mission cycle of the reusable launch vehicle. Part of the functionality of SAVMOS is the maintenance, integration, and launch pad operations simulation and test (MILEPOST) model. MILEPOST allows the user to evaluate candidate designs and perform tradeoff studies for the impact of design characteristics on regeneration time and support personnel requirements. We discuss MILEPOST development and present insights on process time and workforce sizing for several design alternatives.

Nomenclature

n = number of trials in a binomial experiment, where each trial represents a single replication of a simulation model
p = probability of failure in a single binomial trial
R = reliability (probability that a user interface correctly translates a given design decision into a simulation model)
R_1 = lowest acceptable level of system reliability
R_2 = highest unacceptable level of system reliability
r = number of observed failures in n trials of a binomial experiment
X = random variable that counts the number of failures (incorrect design translations) in n trials
α = type 1 error (rejecting a null hypothesis, given it is true)
β = type 2 error (failure to reject the null hypothesis, given it is false)

I. Introduction

SPACE-BASED technologies such as the Global Positioning System, high-bandwidth communications, and satellite imagery have been successfully employed in military operations for over 30 years. As a result, the Department of Defense is interested in developing a quick-response capability to deliver payloads into orbit in response to national defense needs. Quick-response delivery for a reusable military launch vehicle (RLV) is defined as both the ability to achieve launch within 24 h of an identified requirement, and the ability to launch again within 24 h of mission completion. Essentially, the U.S. Air Force (AF) is exploring the development of an unmanned RLV that can operate in an aircraftlike manner. After performing an analysis of alternatives,** the U.S. Air Force determined that the most cost-effective vehicle is a two-stage-to-orbit hybrid with a reusable first stage and an expendable second stage. This vehicle is currently in the early stages of planning and design.

Past experience and current engineering disciplines suggest that adopting a comprehensive view of the systems comprising an aerospace platform early in and throughout the design process is critical to its success over the span of its life cycle. Specifically, as Russell et al. [1] and Kline and Bachman [2] have identified, it is critical to address support issues such as spare parts and maintenance requirements early in the design process of space vehicles. Early planning for logistics concerns allows designers to assess the feasibility of design alternatives or establish preference in design alternatives from a logistics perspective, as well as to identify areas in the design where improvement in reliability or maintainability can yield significant life cycle cost savings [2]. Researchers have used simulation models to analyze launch vehicle ground operations and their associated logistics issues for years. Most of these models were built by and/for the National Aeronautics and Space Administration (NASA) and focus exclusively on shuttle operations or are heavily influenced by shuttle data. Although these models are extremely useful for analyzing shuttle operations, they are limited by the shuttle mind-set and are of questionable use for analyzing potential RLV operations.

The U.S. Air Force Research Laboratory (AFRL) developed the space access vehicles mission and operations simulation (SAVMOS) suite of tools [3] to assess hypersonic launch vehicle

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**Hayes, P., Presentation on United States Space Security Strategy, NATO Defense College, Rome Italy, 17 September 2007, http://www.ndc.nato.int/news/sc111/A1/06-Space%20Security%20&%20Strategy%20-%20Hays.pdf [retrieved 20 October 2008].

concepts in terms of mission planning, launch and space maneuvers, military operational missions, and launch vehicle return flight profiles. To capture the additional functionality of assessing ground support operations, AFRL sponsored the Air Force Institute of Technology to develop a method for assessing flight vehicle design implications on ground support resources, tasks, and their associated sequencing necessary for *recovering*, *maintaining*, and *integrating* (i.e., *regenerating*) a candidate RLV between flights. In response, we first developed a conceptual flow for RLV regeneration actions from existing support processes for the shuttle, military aircraft, and existing expendable launch vehicle ground processes. We then translated the resulting conceptual flow and associated workforce requirements into a discrete simulation module we titled the maintenance, integration, and launch pad operations simulation and test (MILEPOST) model. In this paper, we first describe our approach for developing and validating the ground regeneration conceptual workflow and associated simulation model. We then discuss our process for estimating the associated support workforce requirements, and conclude with an experimental design presenting some insights on vehicle design and workforce composition.

II. Background

In 1982, less than a year after the shuttle began operational service, NASA initiated a modeling effort to analyze the feasibility of different launch schedule options. NASA experienced unexpected delays in shuttle processing and wanted a tool to help them develop a schedule that more closely reflected true regeneration capabilities. The model developed by Wilson et al. [4] was named the shuttle traffic evaluation model (STEM). STEM was an early model and suffered from a lack of historical data. Although it did demonstrate that shuttle operations would take longer than originally expected, it still estimated some regeneration times as low as 28 work days, a capability that NASA approached in the 1980s but was never able to reach.

Shuttle Ops is a more recent shuttle simulation model that accurately mirrors true shuttle regeneration capability. In 1999, NASA was evaluating the feasibility of increasing the shuttle flight rate from 7 to 15 flights per year. NASA needed to know which existing resources could handle the increased flight rate and which resources needed supplementing. Discrete event simulation was chosen as the tool to answer this question, due to the large number and complexity of processes involved with shuttle regeneration. In a Space Act agreement, NASA and the University of Central Florida developed the Shuttle Ops model [5] using the Arena discrete event simulation software application. The developers collected and analyzed historical data on task completion times for shuttle ground processing activities, fit this data to probability distributions, and assigned them to processes within the Arena model. Their attempt to capture the myriad of activities that make up shuttle regeneration was a significant task and resulted in nearly 1000 Arena program modules in the final model. The developers verified and validated the model by comparing model output to actual historical data. Statistical comparison of certain model outputs (e.g., flight rate per year and time spent on pad) with representative historical data validated the model. Even though NASA gave up the idea of increasing the shuttle flight rate before completing the model, the tool was still used successfully to model other scenarios such as mothballing a shuttle orbiter or closing shuttle facilities.

More recently, NASA used the Shuttle Ops model to create the manifest assessment simulation tool (MAST). MAST [6] estimates probabilities of completing shuttle launches according to shuttle manifests, considering starting and completion times for major shuttle activities, such as Orbiter maintenance, vehicle assembly, and launch pad operations. MAST was used to predict the probability of achieving the planned number of shuttle launches before shuttle retirement in 2010.

NASA engineers also developed a simulation model for application to any type of launch vehicle. The Generic Simulation Environment for Modeling Future Launch Operations (GEMFLO) [7] was developed in conjunction with NASA's Space Launch Initiative, which studied different RLV design alternatives as a replacement for the space shuttle. NASA developed GEMFLO to estimate flight rates and other capabilities for competing RLV designs. GEMFLO also runs in Arena software and uses a visual basic graphical user interface (GUI). The main benefit of GEMFLO is that it is generic and usable to analyze any RLV design without any model modification. One model is used to evaluate all vehicle designs instead of building a separate model for each vehicle design. Accordingly, the model relies upon a large amount of user input for estimated activity process times and other capabilities. GEMFLO takes user-input probability distributions and other information and then populates the Arena model with this data. GEMFLO provides outputs such as estimates of vehicle flight rate per year and vehicle regeneration time. The MILEPOST model is in many ways similar to GEMFLO. As with GEMFLO, our simulation is generic, that is, the same model can be used to analyze different vehicle designs and different ground operation variations. However, our model differs from GEMFLO in that it decomposes recovery, maintenance, and prelaunch operations into much greater detail than is provided in GEMFLO. The purpose of our research is to analyze launch operations in a military environment, where a quick response to military contingencies is necessary. Because U.S. Air Force requirements dictate RLV turnaround within a matter of hours, even processes that take only minutes are important to analyze. GEMFLO, although a significant modeling accomplishment in its own right, does not break higher level regeneration processes down into the detailed processes that are required for such a time-savings analysis. Our work, for example, separates higher level processes such as *vehicle integration* and *launch pad operations* into their basic components so that model users can more accurately determine the use of time.

Rooney and Hartong [8] developed an Arena-based simulation model that estimates maintenance task completion times for RLVs. As with GEMFLO, their model also includes a visual basic GUI, and they implemented a clever method of storing and inputting particular RLV design data via spreadsheets. The user inputs vehicle design parameters, such as amount of thermal protection system tile area and other resource and job sequencing information. The model feeds these inputs into an Arena-based model and estimates total turnaround time and turnaround time for specific vehicle subsystems. This model's parametric input design enables it to readily accommodate a variety of design scenarios. However, their model does not include detailed postflight recovery activities, nor was it validated by the diversity of aircraft maintenance and space vehicle experts that assessed our work.

III. MILEPOST Model Development

The MILEPOST regeneration workflow activities [9–11] were derived from existing ground support operations for B-2 bomber and F-16 fighter aircraft, Delta IV and Atlas V expendable launch vehicles (ELV), the Minuteman III intercontinental ballistic missile (ICBM), the Zenit 3SL sea-based launch vehicle, and NASA's space shuttle. We chose these platforms for their ability to demonstrate operations for a variety of potential launch vehicle ground support processes, such as horizontal or vertical stage integration, erecting mechanisms built into the launch pad or the vehicle transporter, and aircraftlike turnaround operations. The shuttle was chosen because it is the only operational reusable launch vehicle that exists today. We selected the Atlas V and Delta IV because they are recent additions to the U.S. expendable launch vehicle fleet and represent their most advanced technologies and concepts for prelaunch operations. The Zenit 3SL is appropriate because rapid prelaunch operations are integral to its design. Finally, the B-2 represents the only heavy load-capable aircraft with the complexity and intermittent usage typical of a space vehicle, and the F-16 provides a probable lower bound on RLV recovery time after landing. We then combined this information with our best estimates of what an RLV ground operations sequence will or will not include. We used an iterative approach by starting with a simple conceptual network of basic RLV ground operation events and added more detail to those networks as more knowledge was gained.

A Delphi panel, made up of a diverse group of aircraft maintenance and space vehicle experts and approved by the research sponsor at AFRL, developed and validated the conceptual workflow. Twenty-one senior-level government and civilian personnel from NASA, AFRL, the U.S. Air Force Aeronautical Systems Center, the U.S. Air Combat Command, the U.S. Air Force Space Command, and one aerospace company made up the panel. In particular, we asked the panel to consider the workflow in terms of task identification and sequencing, and to identify any opportunities for conducting different tasks simultaneously. To communicate our workflow to the panel, we created a representation of the flow in Microsoft Visio software. This gave the panel members an easy-to-read format while not sacrificing details that are important to the model's operation. We provided text on each module in the flow as necessary to provide an explanation or to refer the panel member to a subsequent submodel for greater detail. The panel members reviewed the workflow and submitted comments and suggestions for improvement. We then compiled the responses and changed the workflow where there was consensus among the group members. For areas without consensus, we submitted the separate responses anonymously to the entire group along with the updated workflow. Responses from differing viewpoints facilitated a broader understanding of RLV ground operations and allowed us to consider the full spectrum of launch vehicle processing possibilities. Achieving an overall consensus required three Delphi iterations. Figure 1 depicts a high-level representation of the final conceptual workflow. We presented a complete description of the workflow [12] at the Space 2006 conference in San Jose, California.

We then coded the conceptual workflow into a discrete simulation model, using Rockwell's Arena software. For testing, individual activity times sampled triangular distributions, with parameter values obtained from the Delphi panel members or from relevant technical literature (e.g., [13]). A GUI allows a user to easily tailor the model to reflect a desired space vehicle design configuration for simulation. About 50,000 unique RLV design configurations can be accommodated in the model. Even though the model is generic and adapts to many different RLV processing options, it does make some basic assumptions. The model assumes a reusable first stage and expendable second stage to match the AF hybrid launch vehicle concept. It also assumes that liquid fuels are used in both stages and that the vehicle is unmanned. The RLV engine(s) are reusable, with infrequent replacement. Finally, it assumes that the RLV launches vertically and lands horizontally. Figure 2 shows a representative design.

Fig. 1 Candidate RLV design, depicting a vertical takeoff, glide-back approach.

The current model configuration allows only one entity to flow through the model per replication. Each replication is one complete regeneration cycle for a single mission. Each simulation entity represents a requirement to launch an RLV mission, and seizes resources (such as a first stage, maintenance hangar, or launch pad) as it proceeds through the regeneration operations sequence. In some places cloning the launch requirement entity enables multiple processes to occur in parallel. A set of design decisions initialize the model that collectively determines a mission entity's path through the model. The model's primary output estimates the regeneration time probability distribution for restoring the RLV between consecutive flights.

Model verification involved a series of tests to examine whether all possible RLV designs (entity trajectories dictated by specified network instantiations) were achievable, and whether the model would respond predictably to input changes. To verify that each of the 50,000 entity trajectories was achievable was computationally infeasible for us. Therefore, we used a binomial approach adapted from reliability testing. In our case, reliability was defined as the probability that the model will not fail for a randomly generated entity trajectory. If R is the true model reliability for each test, then

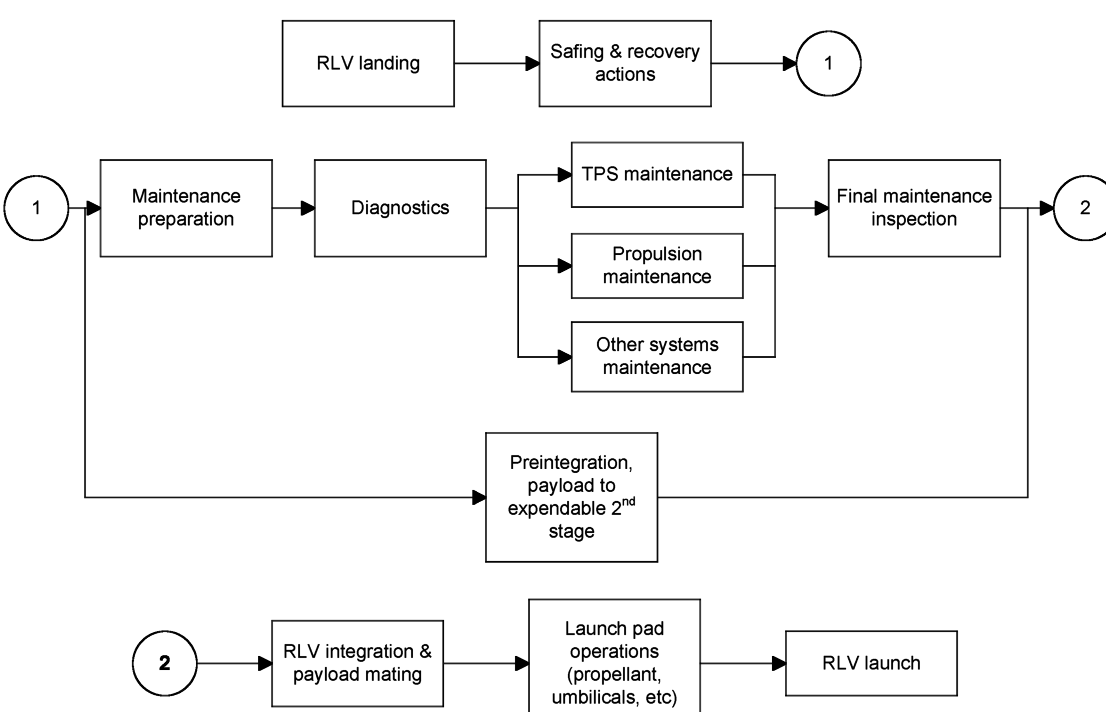

Fig. 2 RLV regeneration activities overview.

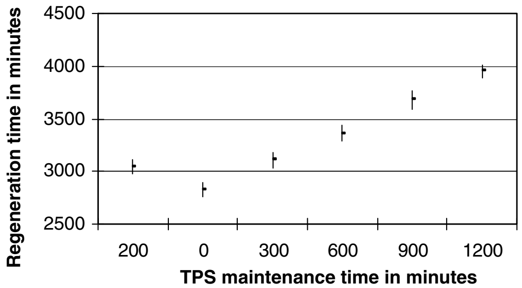

Fig. 3 Test of two-engine configuration.

the number of failures X has a binomial distribution with parameters n and $p = 1 - R$. A binomial test plan specifies the sample size n and the maximum number of failures r, allowed to confidently state that $R \geq R_1$, the desired system reliability. An unacceptable reliability is R_2, where $R_1 \geq R_2$. If $X \leq r$, then we fail to reject the null hypothesis and conclude that $R \geq R_1$. If $X > r$, then we conclude that $R < R_1$. Because of the randomness of sampling, it is necessary to minimize both type 1 (α) and type 2 (β) errors. The relationship between α and β and n and r is expressed in Eq. (1) as

$$\begin{aligned}\sum_{i=0}^{r}\binom{n}{i}(1-R_1)^i R_1^{n-i} &= Pr\{X \leq r \mid R = R_1\} = 1-\alpha \\ \sum_{i=0}^{r}\binom{n}{i}(1-R_2)^i R_2^{n-i} &= Pr\{X \leq r \mid R = R_2\} = \beta\end{aligned} \quad (1)$$

We sought values for n and r that result in acceptable values of α and β, and adapted a reliability acceptance plan given by Ebeling [14] by using the values $R_1 = 0.99$, $R_2 = 0.90$, $n = 50$, $r = 1$, $1 - \alpha = 0.911$, and $\beta = 0.034$ to balance acceptable error risk versus required computational effort.

This particular acceptance plan concludes with 91.1% confidence that $R = 0.99$, if there is at most one failure in 50 trials. Our 50 tests resulted in zero failures, indicating that we are over 91% confident that the model reliability is at least 99%.

We next tested whether the model's output responds predictably to changes in input parameters. For example, Fig. 3 shows how regeneration time for a two-engine RLV configuration changes if the thermal protection system (TPS) maintenance sequence increases from 0 to 1200 min, while all other process times are held constant.

Each point is the center of a 95% confidence interval, based on 30 replications each for six experiment treatments. Note that we allocate 200 min for TPS repair as the "base case," based on discussions with AFRL and B-2 maintenance personnel.

At this stage, MILEPOST allowed a user to make initial design decisions for an RLV and then assess the regeneration time required for a vehicle with those design characteristics. However, the support workforce was modeled as an unconstrained resource. Our next step in model development assessed the manpower requirements generated by an RLV and assigned those manpower resources to the activities modeled, to allow users the ability to investigate the manpower impact of various vehicle design decisions.

IV. Manpower Assessment

We assume that RLV operations and regeneration activities will be performed by AF personnel at an existing AF location, such as Vandenberg Air Force Base, Cape Canaveral Air Force Base, or Patrick Air Force Base. Furthermore, we focus only on the direct support personnel associated with airbase operations; we ignore any additional personnel that may be needed for RLV support at a separate contractor facility or government depot, and we ignore all ancillary base level personnel such as security, lodging, food service, etc. Finally, we assume a baseline operation involving three shifts for 24 h operations for a fleet of six flight vehicles.

AF policy [15] requires that organizations performing similar missions operate under similar organizational structures, allowing for standardization across the AF for operational units. Within an organizational structure, specific unit manpower authorizations may be determined using several methods. The first AF-approved method is a logistics composite model (LCOM) study, in which a simulation of specified operational conditions is used to generate required work center staffing. The second method involves the use of AF manpower standards (AFMS), which define a standardized, sequential assessment of workload factors that units follow to derive required manning. In isolated instances, units may assess manpower requirements based on maintenance man-hour per flying-hour data when the preferred LCOM and AFMS methods are not feasible [16]. Standard AF practice at this time is to derive maintenance group (MXG) requirements from an LCOM study, and all other supporting unit manning requirements from AFMS application.

Our first step in performing an RLV manpower assessment determined whether the MILEPOST activities required for RLV regeneration were supportable under the current structure of AF technical expertise, defined by the standardized listing of AF specialty codes. Our comparison of AF specialty codes against all of the MILEPOST activities revealed several areas of shortfall, in which the required level of expertise was not reflected in any current AF specialty code knowledge requirement. These areas of shortfall occurred in areas dealing with hazardous gases and liquids, specialized ground support equipment, and drag chutes. However, recent historical precedent with B-2 aircraft maintenance reveals that shortfalls in required expertise can be addressed through specialized training programs for personnel in already-established specialty codes, and may not require an immediate change to the AF specialty code structure [17].

Next, we compared the mission statements and support capabilities of existing AF aircraft, ELV, and ICBM logistics organizations to the RLV mission requirements. We found that the B-2 stealth bomber's logistics organization provides the best capability to support RLV ground operations. The B-2 is the closest heavy load-capable aircraft to a space launch vehicle in terms of expected complexity and intermittent usage [17]. As a result, the B-2 LCOM-derived support manning requirements provided our foundation for estimating RLV manpower authorizations. Our final step identified the manpower implications of specific differences between the B-2 and a space launch vehicle. First, we removed from the totals those workcenters in the B-2 LCOM assessment that would not be required by an RLV. These removed workcenters addressed requirements for aircrew, deployment commitments, multiple flying squadrons, and precision-guided or nuclear munitions. Next, we adjusted the overhead functions within the affected squadrons to reflect the new support requirements. In sum, of the 1536 LCOM-derived personnel required to support B-2 operations, 1092 would also be required to support RLV operations [17]. However, this initial estimate does not account for significant differences between the shuttle, B-2, and the RLV such as relative fleet size, system complexity, 24 h operations, etc. To reconcile these differences, we established the parametric relationships shown in Table 1, based on comparisons between Shuttle Orbiter maintenance operations, as reflected in documented maintenance man-hours by activity, and B-2 aircraft maintenance operations, reflected in LCOM manpower requirements by workcenter. We then modified our initial estimate by successively applying each parameter multiplicatively to the appropriate workcenter personnel quantity. Michalski [17] provides a complete description of our process and results.

Our first parameter accounts for two-shift versus three-shift operations. Our second parameter reconciles the relative contribution of individual workcenters to total shuttle maintenance versus the relative contribution of individual workcenters to total B-2 maintenance. Overall, the relative contributions of individual shuttle maintenance activities agree fairly well to those of individual B-2 maintenance workcenters, but several significant disparities exist. First, the manpower implications of a shuttlelike thermal protection system strongly support minimizing TPS requirements, which we address in a separate sensitivity analysis in this section. Second, we noted a 12% higher percent contribution for shuttle liquid propulsion maintenance versus the associated B-2 propulsion maintenance and research engineer workcenters, and so our second (propulsion)

Table 1 Parametric relationships

Parameter	Coefficient values	Source
No. of shifts	2, 3	LCOM study [17], RLV responsiveness requirements
Propulsion	1.12	Comparison of Orbiter [13] and B-2 maintenance data [17]
Surface area	2.5, 2.0, 0.5	Assessment of vehicle sizes from Orbiter [8] to Kistler K-1[a]
Relative complexity	1.5, 2.0, 2.5	Comparison of total shuttle ground processing workforce size to total aircraft ground processing workforce size [13,16][b]
Fleet size	1–7	RLV statement of objectives
Fuel	2, 2.675, 3.5	Shuttle Orbiter main engine fuel load versus B-2 fuel load[c]

[a]"Kistler K-1," http://www.kistleraerospace.com/ [retrieved 21 Feb. 2007].
[b]"Space Shuttle Basics," http://www.spaceflight.nasa.gov/shuttle/reference/basics/index.html [retrieved 18 Jan. 2007]; "The Space Shuttle Launch Team," http://science.ksc.nasa.gov/shuttle/countdown/launch-team.html [retrieved 18 Jan. 2007].
[c]"Space Shuttle Basics," http://www.spaceflight.nasa.gov/shuttle/reference/basics/index.html [retrieved 18 Jan. 2007]; "B-2 Spirit," U.S. Air Force Fact Sheet, http://www.af.mil/factsheets/factsheet.asp?id=82 [retrieved 14 Dec. 2006].

parameter reconciles this difference. The other major disparity is in the arena of shuttle structures, mechanisms, and vehicle handling functions. However, this shuttle function would involve too many B-2 workcenters to determine a specific parametric relationship. Instead, we used our (third) surface area parameter as a surrogate to adjust the B-2 structural repair workcenter. Because the Shuttle Orbiter has approximately 2.6 times more surface area than the B-2, we thus assumed the RLV will be smaller than the Orbiter and rounded down, using 2.0 as our parameter value. Because the actual RLV surface is yet unknown, we established a sensitivity analysis range, bounded by the respective Kistler K-1 and Shuttle Orbiter surface areas.

One of the most challenging differences to capture between B-2 and RLV manning requirements is the greater technical complexity associated with space vehicles over aircraft. When establishing our (fourth) relative complexity parameter to approximate the net impact of this factor, it would be ideal to compare the total number of personnel performing ground support operations between subsequent shuttle launches to the total number of personnel required for B-2 regeneration. However, this information was not available from the United Space Alliance (USA) due to proprietary concerns. In its place, we performed two estimations. First, we compared the approximate total number of USA employees to the B-2 bomb wing, which had a similar scope of responsibilities. Second, we used the shuttle launch crew size to estimate a total workforce requirement for comparison. From this, we calculated a baseline complexity parameter value of 2.0, with sensitivity analysis values set at 1.5 and 2.5.

Our fifth parameter adjusts the total workforce for varying fleet quantities. Our final (sixth) fuel factor compares the shuttle's main engine fuel load to the B-2 to obtain 2.675, and then uses sensitivity factors of 2 and 3.5. In all cases, we assume a linear relationship holds for the six parameters and their respective effects on workforce size. We identified differences in the following areas:

1) The LCOM assessment for B-2 maintenance activities modeled two shifts for 24 h operations in a surge period. The requirement for sustained 24 h operations to maximize RLV responsiveness led to a manpower adjustment to three-shift operations.

2) Propulsion activities formed a greater percentage of total shuttle maintenance workload than for respective B-2 maintenance manning.

3) We expect the RLV surface area, which will particularly impact the structural repair aircraft workcenter, to be different from the surface area of the B-2.

4) We expect the RLV relative technical complexity to be greater than for the B-2.

5) The RLV fleet size, while expected to include six vehicles, was assessed for a range of one to seven.

6) RLV fuel loads will likely exceed the B-2 fuel load.

We then applied these parameters to the appropriate B-2 logistics workcenter staffing. Because most of the parametric relationships included a range of values, we used a factorial experiment design to estimate the manpower requirements for a range of RLV fleet characteristics. The most likely values for each of the parameters established in this research are three shifts, 2.0 times the surface area of a B-2, 2.0 times the relative complexity of a B-2, a fleet size of six vehicles, and 2.675 times the fuel requirements of a B-2. We consider the point estimate corresponding to these values, 1872 personnel, to be our most likely estimate of total required manpower support based on our stated assumptions. Figure 4 shows a decomposition of the principal workcenters and associated staffing. The range of staffing requirements in Fig. 4 for each workcenter represents the support of

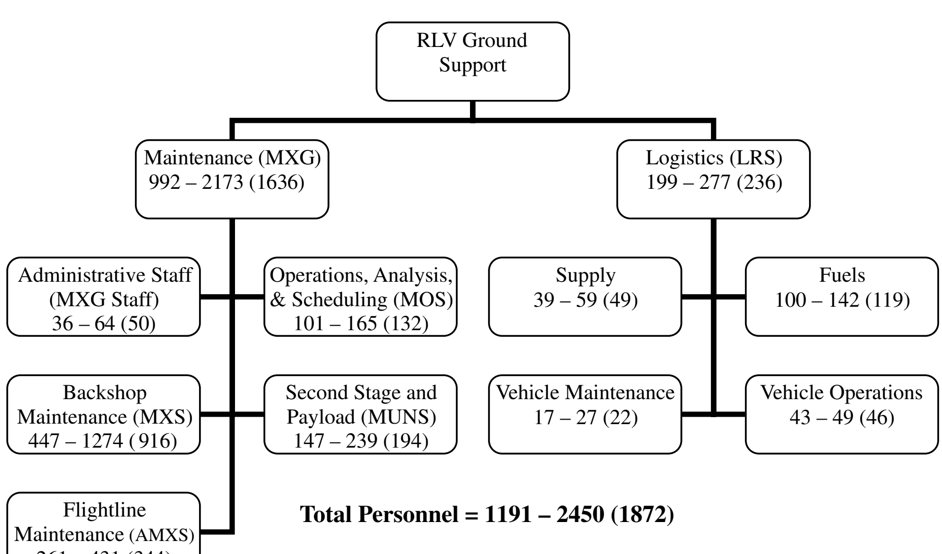

Fig. 4 RLV logistics support organization. Most likely manpower levels are indicated in parentheses.

six RLVs with three shifts of operations with surface area, complexity, and fuel requirements at their lowest, most likely, and highest values. The MSG branch in Fig. 4 generally represents direct labor requirements, while indirect labor tasks are shown in the logistics (LRS) branch.

The flightline maintenance (AMXS) workcenter supporting an RLV fleet will comprise a much smaller percentage of total maintenance operations than for the B-2, while the MXS workcenter will make up a much greater portion of the MXG. The RLV fleet may be much smaller than the B-2 fleet, necessitating fewer flight-line maintenance manning resources, whereas the increased maintenance requirements of the more complex propulsion system and structural elements require increased manning resources in the backshop. In addition, the operations, analysis, and scheduling (MOS) workcenter grows slightly in proportion due to the involvement of the research engineer section in the engineering support element of shuttle propulsion operations. Finally, the second stage and payload (MUNS) workcenter decreases slightly due to reduced maintenance requirements associated with second stages and payloads that are delivered ready to integrate.

It is interesting to compare the level of effort required to regenerate an RLV versus the shuttle and B-2 aircraft. If we assume that an RLV requires about 90 h to regenerate between flights (a MILEPOST output value based on notional, but plausible input data), then 1872 RLV support personnel divided by six flight vehicles equates to 312 persons per vehicle. Dividing this result by three shifts per day gives 104 persons per shift. Finally, 104 persons multiplied by 90 h per mission results in about 9360 support hours per mission flown. In contrast, B-2 support requires 1536 people for 16 flight vehicles. We assume three operations shifts and 15 regeneration hours per mission. Using the same method as for the RLV, we observe 480 B-2 support hours per mission flown. As a final comparison, the shuttle's total ground processing hours per launch were benchmarked in the late 1990s (a period representing the shuttle's highest sustained flight rate) by the United Space Alliance at 525,000 h per flow.[††] Hence, although our estimated RLV regeneration effort is an order of magnitude higher than for the B-2, its unmanned aspect and newer technology will hopefully make it several orders of magnitude easier to regenerate than the shuttle.

Figure 5 illustrates the complete range of manpower requirements from least demanding to most demanding. Approximately 150 personnel could reasonably be expected to support a single RLV, given two-shift operations and low surface area and complexity characteristics. However, it would take over 2000 personnel to support seven RLVs at the high extreme of expected surface area and complexity. The pattern of workforce growth demonstrates that backshop maintenance (MXS) grows proportionately faster than other workcenters, indicating that the greatest manpower requirements per RLV may occur within the MXS function. Therefore, design decisions that improve maintainability, or promote high system reliability, ease of access, or health management systems, can have a significant impact on total manpower requirements.

In addition to estimating the total ground support manpower requirements for an RLV fleet, we also identified technology decisions, such as TPS improvements and integrated vehicle health management (IVHM) system adoption, that can generate significant manpower requirement savings based on the workcenters impacted. The changes in workforce requirements, compared to the baseline best estimate, are illustrated in Fig. 6. A substantial decrease in workforce size is achievable by using an IVHM system that reduces inspection and trouble-shooting requirements by 50%, a capability level that is historically feasible as established on the AF C-17 aircraft program.[‡‡] Such an IVHM system causes the MXS and AMXS functions to reduce proportionately in comparison to the other workcenters, and thus total manpower requirements shrink considerably. Figure 6 also shows the significant increase in manpower that may result if the RLV design includes TPS components similar to those used on the Shuttle Orbiter. Based on these numbers, we encourage RLV designers to consider improved IVHM and TPS technologies to achieve manpower savings.

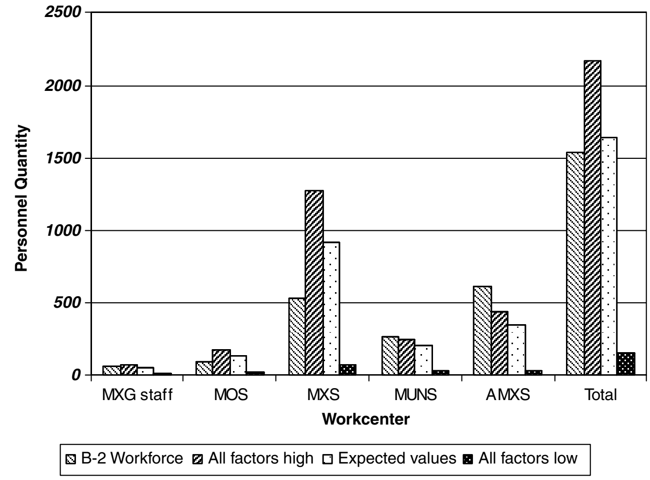

Fig. 5 Range of potential personnel workforce levels based on Table 1 parameters.

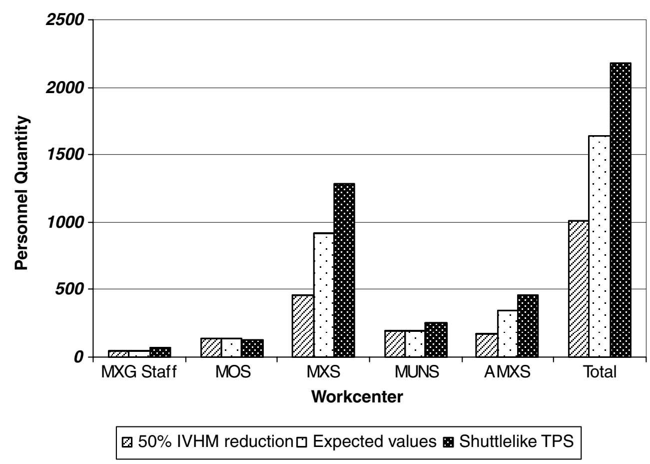

Fig. 6 Impact of IVHM and TPS on RLV manpower requirements.

We thus developed a comprehensive estimate of manpower requirements for an RLV, beginning with an AF support agency for a fleet of aircraft and making adjustments for unique RLV support characteristics. As such, it captures all of the direct labor required for the daily operation of a fleet of six space flight vehicles. In the next phase of research, we translated the workforce composition into appropriate manpower resources for individual MILEPOST activities.

V. Assigning Manpower in the Model

Having established the technical specialties required to support the RLV, each activity in MILEPOST could be assigned to a technical area. We determined the number of technicians required to perform a specific activity by first identifying a corresponding aircraft activity for each MILEPOST activity. We then adjusted the number of AF personnel required to perform that activity by using the appropriate

[††]Gregory, F. D., "Assessment of the SFOC/USA Risk Management Process for Determining Proposed Staff Reductions," Office of Safety and Mission Assurance, 16 Jan. 1998, ftp://ftp.hq.nasa.gov/pub/pao/reports/1998/SFOC_assessment.txt [retrieved 14 April 2008].

[‡‡]Losurdo, M., "Dover Reorganizes for C-17 Mission," AF Link, 8 Feb. 2007, http://www.af.mil/news/story.asp?id=123040329 [retrieved 26 Feb. 2007].

parametric relationship for that technical specialty from our manpower assessment. The result was that each MILEPOST activity is now assigned a number of technicians adjusted for RLV operational characteristics.

The model draws its personnel resources from a separate pool of manpower established for each respective technical specialty. Thus, if the model requires three electrical technicians to perform a repair followed by two electrical technicians to perform a systems check, the model will draw three personnel and then two personnel from the electrical technician pool of labor. The model at this time does not account for different skill levels, such as journeymen versus apprentices, within a technical specialty. If two activities occur in parallel and require the same type of technician, the model will attempt to draw all requirements from the pool. If there is insufficient manpower, the activities will be forced to occur in series. In this manner, it is possible to see the impact of increasing manpower levels on regeneration time for a given vehicle.

Although the model will currently output a total number of required technicians for each specialty, this does not reflect total workforce requirements because MILEPOST does not capture overhead requirements such as supply support, scheduling, and supervisory and management positions. As a result our manpower assessment research [17] still provides a better representation of an RLV ground support organization. However, the simulation capability allows us to compare the regeneration times of various vehicle configurations under varying levels of manpower support.

VI. Experiment

Table 2 summarizes the design decisions available in MILEPOST and the design characteristics chosen for this experiment. We used a full-factorial experiment to determine which design alternatives in MILEPOST presented the best regeneration times under varying levels of manpower constraints.

We selected three particular RLV design decisions (factors) for evaluation: preintegration, location, and configuration. Preintegration addressed whether the second stage and payload were mated before integration with the RLV. Location referred to whether the RLV, second stage, and payload underwent final integration on the launch pad or at an off-pad facility. Configuration addressed whether the three vehicle components would be integrated horizontally or vertically. All other RLV design decisions in the model were held constant. We used aggregate manpower as the fourth factor for our experiment.

We established the initial manpower level by running the model with unconstrained manpower resources to assess the maximum requirement for each technical specialty that occurred at a point in time during the simulation. We used these maximums as the minimum manpower requirement (denoted as 100% manpower) for each technical specialty, and deemed them the experiment baseline. We then evaluated the design alternatives at four additional levels of manpower, established at increases of 125, 150, 175, and 200% of the baseline requirements.

The three design decisions (indicated by bold text in Table 2), if evaluated at each of their possible levels, yield eight possible factor-level alternatives, as shown in Table 3. However, we did not examine alternatives 1 and 5 because our vertical launch assumption implies that integration on pad would be performed vertically. As a result, six vehicle design alternatives remained for assessment at the five tested manpower levels. We tested each design alternative-manpower level treatment with 30 MILEPOST simulation replications, resulting in 30 sets of 30 regeneration times. Table 4 ranks the 30 treatments in order of lowest to highest average regeneration time, based on a Tukey–Kramer highly significant difference (HSD) test at $\alpha = 0.05$.

Table 2 MILEPOST test decisions

Design decision	Test value	Other values
Preintegration	**Yes**	**No**
Location	**On pad**	**Off pad**
Orientation	**Horizontal**	**Vertical**
Off-pad integration locations	Integration facility	Maintenance bay
Engine configuration	Modular	Repaired on RLV
No. of RLV engines	4	1, 2, 3, 5, 6
Hypergolic fuels required	No	Yes
Ordnance required	Yes	No
Where is ordnance loaded (as applicable)	Integration facility	Launch pad
Erecting mechanism (as applicable)	Separate mechanism	Part of transporter
Location of payload integration (as applicable)	Integration facility	Launch pad
Type of connections	Propellant & electrical	None, propellant only
Vehicle uses rocket propellant (RP) fuel	Yes	No
Stages that use RP (as applicable)	Stage 1 only	Stage 2, stages 1 and 2
Propellant loading	Strict serial	Stages in parallel, stages and fuel & oxidizer in parallel
Is RLV taxi capable?	Yes	No
Is auxiliary power unit shutdown automatic?	Yes	No
Can RLV return with external stores?	No	Yes
Is purging and inerting required?	Yes	No
Is external ground cooling required?	Yes	No
Are MPS and RLV protective covers required?	Yes	No

Table 3 Experimental design

Design alternative	Preintegration?		Integration on pad?		Integration orientation
	Yes	No	Yes	No	
1	**×**		**×**		**Horizontal**
2	×		×		Vertical
3	×			×	Horizontal
4	×			×	Vertical
5		**×**	**×**		**Horizontal**
6		×	×		Vertical
7		×		×	Horizontal
8		×		×	Vertical

Table 4 Tukey–Kramer HSD test. Regeneration times ordered by mean, from least to greatest. Treatments not connected by the same letter are significantly different ($\alpha = 0.05$)

Treatment																	Mean regeneration time, h
3–175%																P	82.92
3–200%																P	82.95
3–150%																P	83.44
2–175%																P	83.52
2–200%															O	P	83.55
2–150%															O	P	84.03
3–125%														N	O		84.84
2–125%													M	N			85.44
7–200%												L	M	N			85.84
7–175%												L	M	N			85.88
3–100%											K	L	M				86.19
7–150%										J	K	L	M				86.43
2–100%									I	J	K	L					86.79
4–175%								H	I	J	K						87.19
4–200%								H	I	J	K						87.23
4–150%								H	I	J							87.71
7–125%								H	I	J							87.73
6–200%								H	I								87.77
6–175%							G	H	I								87.81
6–150%						F	G	H									88.36
8–200%					E	F	G										89.09
4–125%					E	F	G										89.12
8–175%					E	F											89.13
7–100%				D	E	F											89.41
6–125%				D	E	F											89.66
8–150%			C	D	E												89.68
4–100%		B	C	D													90.47
8–125%		B	C														90.98
6–100%		B															91.33
8–100%	A																92.65

At the 100% (baseline) manpower level, alternatives 2 and 3 were statistically similar but collectively better than the other four alternatives. Alternatives 2 and 3 also dominated all other alternatives for manpower levels set at 150% or higher. Conversely, design alternative 8, at the baseline manpower level, was outperformed by all other treatments. Table 4 also shows that although there is significant regeneration time benefit to increasing manpower levels up to 175% greater than the baseline, there is no further significant benefit to doubling the workforce. The 175 and 200% manpower levels were statistically similar for all six design alternatives.

Figure 7 depicts the same Tukey HSD test results, but now grouped in the six respective design alternatives from Table 3. Several clear trends collectively emerge from Table 4 and Fig. 7: first, preintegration of the second stage and payload consistently yielded lower regeneration times. Second, Fig. 7 shows that the impact of manpower level on regeneration time was similar across all six design alternatives, with diminishing returns occurring after the 150% manpower level. The least time-efficient configuration (treatment 8–100%) represents an RLV that would require off-pad, vertical integration of both stages and payload using baseline personnel workforce levels. The most efficient RLV configurations result when designers use vertical or horizontal integration, as long as vertical integration occurs on the launch pad and the second stage and payload are preintegrated. Additionally, RLV with these design characteristics achieve their maximum manpower impact at the 50% increase level, effectively allowing them to accrue the same improvements in regeneration time that the other configurations achieve with a 75% increase in manpower.

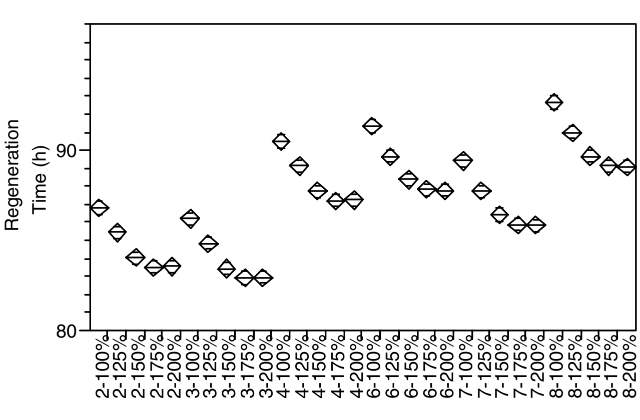

Fig. 7 Design alternatives 2, 3, 4, 6, 7, and 8 from Table 3, each evaluated at 100, 125, 150, 175, and 200% of the baseline manpower level. $\alpha = 0.05$. Each diamond represents a 95% confidence interval of the respective treatment mean. Overlapping diamonds are statistically similar.

VII. Conclusions

Our estimate of logistics support manpower requirements, given 24 h operation of six RLV stationed at an existing base such as Patrick or Vandenberg Air Force Base, varies between approximately 1200 and 2400 personnel depending on RLV size and complexity, with a most likely value of just under 1900 personnel. As a lower bound, a single small RLV would require about 150 personnel to support two-shift operations. Although some training and manning shortfalls exist in expected areas of expertise, we believe they can be adequately addressed without driving fundamental changes in the AF support manpower structure. Although history will almost certainly prove our point estimates for RLV support manpower to be off, and it is hoped too high, we believe they do represent reasonable order-of-magnitude values, given the current lack of detail on RLV vehicle design and operations concepts. Aerospace vehicle history [18] strongly suggests that design decisions in the early stages of RLV development will have a significant impact on life cycle requirements for personnel support and overall program cost. For example, our manpower assessment research indicates that both TPS and IVHM technologies will significantly impact total workforce requirements. At the same time, improvements in system reliability can reduce backshop maintenance personnel requirements, which will likely compose the greatest portion of the total workforce.

Simulation modeling using the established MILEPOST model provides an opportunity to estimate the regeneration time and manpower impact of various design decisions. It is important to note that MILEPOST does not generate total manpower requirements for a given design decision; rather, it allows the designer to assess the relative manpower impact of a design characteristic and choose configurations that have a lower manpower impact.

Our Sec. VI experiments suggest that preintegrating second stages and payloads can yield significant savings in both manpower and regeneration time. RLV designers should consider avoiding configurations which require vertical integration in an off-pad facility, but may employ either vertical or horizontal integration as long as vertical integration occurs on the launch pad. (A notable counterexample is the Atlas V evolved ELV, which is integrated vertically off-pad today.)

Logistics planners should recognize that increasing manpower can only improve regeneration time up to a certain level, indicated for these vehicle configurations between 150 and 175% of baseline manpower requirements. Additional time savings must come from vehicle design characteristics. Of the six design alternatives tested, a design that incorporates off-pad preintegration and final integration that occurs vertically on the launch pad or horizontally at an off-pad location provides the best regeneration times, and furthermore allows optimal results at a 50% increase over baseline manpower requirements.

Although our Sec. VI experiment tested only a small percentage of the possible vehicle configurations available in MILEPOST and did not formally investigate any potential interactions between the factors used, it demonstrated the model's capability to provide a useful assessment of design alternatives with respect to both configuration and manpower requirements. Our research continues to improve processing times and personnel requirements fidelity within MILEPOST. Our current work focuses on modeling activity times as parametric functions of key vehicle design variables. As higher-fidelity design data become available for the RLV, further improvements to MILEPOST will be feasible. In particular, we wish to refine the parametric relationships of Table 1. For example, the relative complexity parameter is currently a ratio of shuttle ground support workforce size versus the corresponding B-2 value. This parameter is decomposable into function or technology-specific subparameters. Also, the relationships between the six parameters and their respective effects on workforce size may be nonlinear, particularly over larger ranges of possible coefficient values.

A further limitation of our work is that we have not yet modeled the effect of successive, possibly overlapping RLV missions on resource contention, queuing behaviors, or regeneration time. Our next research phase will involve a larger designed experiment to better explore the relationships between flight rates, resource capacity, personnel staffing, and operations and support cost.

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