

A FRAMEWORK FOR ASSESSING THE REUSABILITY OF HARDWARE (REUSABLE ROCKET ENGINES)

INTRODUCTION

Within the past few years, there has been a renewed interest in reusability as it applies to space flight hardware. Commercial companies such as Space Exploration Technologies Corporation (SpaceX), Blue Origin, and United Launch Alliance (ULA) are pursuing reusable hardware. Even foreign companies are pursuing this option. The Indian Space Research Organization (ISRO) launched a reusable space plane technology demonstrator and Airbus Defense and Space is planning to recover the main engines and avionics from its Advanced Expendable Launcher with Innovative engine Economy [1] [2]. To date, the Space Shuttle remains as the only Reusable Launch (RLV) to have flown repeated missions and the Space Shuttle Main Engine (SSME) is the only demonstrated reusable engine. Whether the hardware being considered for reuse is a launch vehicle (fully reusable), a first stage (partially reusable), or a booster engine (single component), the overall governing process is the same; it must be recovered and recertified for flight. Therefore, there is a need to identify the key factors in determining the reusability of flight hardware. This paper begins with defining reusability to set the context, addresses the significance of reuse, and discusses areas that limit successful implementation. Finally, this research identifies the factors that should be considered when incorporating reuse.

REUSE/REUSABILITY DEFINED

In simple terms, reuse or reusability can be defined as: the repeated use of a product. According to this simple definition, all rocket engines are reusable since they are designed for repeated starts. Heald believes “launch vehicle components are inherently reusable, usually tested for at least 10 times their expected usage; no parts are designed to fail after one flight [3].” However, these multiple starts were used for ground testing not flight. Engines such as the F-1 (20 starts, 2250 seconds) and the J-2 (30 starts, 3750 seconds) are sometimes referred to as reusable engines even though these engines were used for hotfires (i.e. testing) only [4]. The ability to restart an engine does not constitute a reusable engine. Therefore, for the purposes of this paper, reusable is defined as any spaceflight hardware that is not only designed to perform multiple flights, but actually accomplishes multiple flights. Although a component can survive numerous tests, it must be specifically designed for reuse to survive the reentry environment and still have enough integrity remaining to be readied for the next mission. It takes more than intent for a system to be considered reusable. Systems cannot be considered reusable until they have been validated (i.e. retrieved, recertified, and reflown). In other words, only when a system has been used multiple times in the application for which it was designed can be it then classified as truly reusable.

Furthermore, reuse can be categorized as either fully reusable or partially reusable. As the name implies, fully reusable means that the entire system is reused. When only parts of a system are reused, then it would be classified as partially reusable. Even the Space Transportation System (STS), which consisted of the Space Shuttle, SSMEs, SRBs, and External Tank (ET) would be considered partially reusable by this definition. The ET was discarded in the ocean while the other elements were flown multiple times after being refurbished and/or serviced.

IMPORTANCE OF REUSE/REUSABILITY

Reusing expensive flight hardware conserves resources because time and money can be saved by not reproducing hardware [5]. The logical thought process leads us to believe that reusing an item should be cheaper than purchasing and/or manufacturing a new one. One reason for this way of thinking is that both airplanes and automobiles are used repeatedly for years, staying in service until they are no longer needed or desired. Replacing aircraft and cars after each use would make them cost prohibitive for most users, passengers and drivers alike. Reliability and engineering confidence for aircraft has increased over numerous years and now allows routine flights to carry passengers around the world [6]. Having access to extensive databases has enabled the development of maintenance scenarios that support quick turnaround. It stands to reason that if launch vehicles are reused, they will eventually support a flight rate that will make the price point reasonable for more users. As companies continue to pursue reuse over the years, databases can be built to serve as the foundation for the next generation of reusable hardware.

ROADBLOCKS & LIMITATIONS OF REUSABILITY

“We do the hard stuff”, is a commonly said around NASA. Space exploration is not an easy feat and qualifies to be considered “hard stuff”. Reusability fits into that same category; it is neither easy nor free. Reuse requires an upfront investment and planning must start in the conceptualization phase [7]. Although the SSME was designed to be a reusable engine, performance was the primary design driver; thereby adding complexity. Just because a system is designed for reuse does not mean that it is operationally efficient or simple, especially if performance is the driving requirement. Complex systems have more failure modes, are harder to maintain and prone to more human error. Making hardware (vehicles, engines, etc.) reusable adds another level of complexity too. These additional nuances include the ability to repeatedly survive the harsh reentry environment, thermal protection, more robust structures, tanks designed with higher safety factors to minimize stress damage, and extra propellant to perform deorbit maneuvers none of which are required of expendable counterparts [8]. This results in additional failure modes. For reuse to be more effective, turnaround times must be drastically reduced from the Space Shuttle’s required maintenance of two to three months. As articulated by Weegar, “the traditional way of thinking in the rocket industry has been to focus on performance driven parameters such as “propellant types, sea level thrust, specific impulse, chamber pressure, and main engine weight” [6]. Vehicles and associated hardware, like the main engine, that are designed for performance are “inherently difficult to maintain and are predisposed to the introduction of human mistakes [6]. As stated earlier, the SSME was a reusable engine that was designed for performance rather than for supportability [9]. Extensive and costly maintenance are the inherent by-products of placing the primary emphasis on performance. After each flight the SSME must be removed from the vehicle for maintenance. It takes more than 20,000 hours of direct and indirect labor and two months to service the engines [10]. “Operability and supportability are inherent products of the design process and there is no way to build them in later after delivery [6].” Failure to factor in these two elements (operability and supportability) early in the design process lends credence to the old axiom “pay me now (design costs) or pay me later (higher maintenance costs).

With reusability being in its infancy in the space flight sector, standards for reuse have not been developed. This obvious omission poses problems in that the benefits of reusability are difficult to measure [7]. Lately, there has been a renewed interest in the pursuit of reusability within the space flight industry across the world. These industry standards may eventually become a reality if government entities and commercial companies continue to pursue reusability. However, if this effort to achieve reusability is abandoned, as it has been in the past, it will be difficult to develop extensive databases for the space flight, much like those of the aircraft industry that span over 100 years.

FACTORS TO CONSIDER WHEN IMPLEMENTING REUSE/REUSABILITY

Ideally, reuse is successful when the refurbishment cost is less than the acquisition cost. It is also important to understand which components are candidates for reuse or replacement. The realization is that all component cannot be successfully reused [7]. If an objective of reuse is to lower cost of access to space, then it seems practical to consider high dollar assets for reuse. The main engine, is one of the most expensive components on a launch vehicle whether expendable or reusable. The first stage engine on the Atlas 401 is the most expensive component on the vehicle [11]. Therefore, it is beneficial to focus on reusing the most expensive hardware. By reusing these components, the cost is amortized over the operational life of the component.

1. REUSABILITY REQUIREMENTS IMPLEMENTED AT THE CONCEPTUAL STAGE

As a design matures through the life cycle phases, design changes and the incorporation of new features cause significant increases in cost when added later. For reusability to be efficaciously incorporated in any design, the requirement must exist from the beginning (i.e. conceptual phase). Having reusability as a requirement forces a different way of thinking and influences design decisions. When reusability is the primary goal, the operability should be the next requirement instead of performance. For reusability to be successfully implemented, turnaround time must be accomplished in days, or better yet in hours rather than months, like the Shuttle, SSMEs, and SRBs [6]. The importance of efficient operability is best summarized by Bowcutt, "Life cycle cost is driven more powerfully by operational parameters such as turnaround time, than by performance parameters such as engine Isp and dry weight. For example, it would take an approximate 30% change in engine Isp, or 100% change in vehicle dry weight, to equal a 15-day change in turnaround time" [12]. In this instance, the parameter that enhances reusability (better reset time for launch vehicles) also has more influence on cost than performance parameters.

2. CONTINUOUS TEST PROGRAM

Testing is critical in the development of space flight hardware and validates analytical models. Even after the development programs ended, the military continued testing engines to improve characteristics such as life, reliability, producibility, and operability [13]. Similarly, the SSME program continued testing throughout its operational life. This sustained test program enabled the SSME to increase reliability, incorporate modifications, and identify and resolve problems [14]. Thus, the importance of maintaining an active test program cannot be over emphasized. An active test program, coupled with actual flight data, enhances the reliability of the hardware.

3. MINIMIZE POST-FLIGHT INSPECTIONS & SERVICING

The ultimate goal is to severely reduce or totally eliminate between flight maintenance. This standard practice in the aircraft industry leads to quick turnaround for flights. Downtime is a severe crippler to reusability. To offset this effect, shorter duration, less expensive maintenance can prove beneficial by leading to quicker turnaround time between launches. It is much easier and less costly to get an oil change in an automobile than to completely overhaul its engine. Applying that logic to rockets, between flight maintenance should limit inspections to cursory checks rather than intrusive inspections inviting the possibility of collateral damage to the hardware. Steps to enhance reuse include:

- Provide designs that allow minimum periodic maintenance
- Design-in preventive maintenance to reduce unplanned repairs

- Include integrated health monitoring to identify areas to service between flights
- Use off-the-shelf component whenever possible
- Look for opportunities to incorporate common components [15]

Incorporating these steps will increase the viability of reusable designs. This approach simplifies both design and maintenance by minimizing hands-on touch labor, which is inherently costly, reducing the number of maintenance tasks, and decreasing the amount of corrective actions required between launches.

One must be aware of the effects of propellants as well. Propellant selection has either a positive or negative influence on maintenance activities. As mentioned earlier, hydrocarbons are known for coking [16]. When using soot-generating propellants, an awareness must be maintained that eventually removing the resulting residuals may be required. According to Marlow, “an ox-rich cycle engine, with its clean preburner combustion exhaust, offers an advantage over a soot-producing fuel-rich gas generator cycle engine in reusable engine applications: no need for the added ground crew, support equipment and operational activities associated with removing soot deposits after each engine firing” [16]. This added maintenance has a negative impact on turnaround time. When it comes to reusability, clean-burning fuels offer a clear advantage over soot-producing fuels by increasing operability. However, it is possible to design engines to minimize the effects of coking. The RS-84 engine, part of a technology demonstration program for the Space Launch Initiative (SLI), incorporated specific design features to limit the effects of “sooty build-up on” its components [17]. Every aspect of the engine design should be evaluated for its effect on reuse [16] [18]. This reinforces that reusability must be a requirement from the beginning to influence decisions that enhance the design, whether the focus is propellant selection or engine design.

4. EASY ACCESS

Life cycle costs are heavily influenced by operational parameters such as turnaround [12]. Reusable hardware should be designed for operational efficiency to enhance maintenance, reduce turnaround time, and lower life cycle cost. Beginning in the conceptual stage, requirements must focus on operability and supportability in addition to performance. With this mindset in the early stages of the design, components with higher failure rates and requiring more maintenance should be strategically located for easy access. It is evident that performance-driven designs such as the SSME are not “operationally effective”, which lead to extensive and complicated maintenance not conducive to quick turnaround [6]. Designs that are not operationally inefficient cost both time and money.

A significant amount of operations and support cost can be attributed to post-flight inspections and maintenance [9]. Assembly and disassembly must be simplified to improve turnaround time. Unlike the B-1 jet where it only takes 2.5 hours to remove the F101 engine, the SSME requires up to four months to be serviced [13] [19]. Complex labor-intensive interfaces such as bolted joints with torque specification and patterns should be replaced with quick connect/disconnect fasteners to facilitate assembly and removal [9]. Reducing the number of interfaces (electrical, structural and mechanical), between the vehicle to engine would eliminate potential failure modes (inherent and induced) [13]. Incorporating these features will reduce touch labor.

5. MINIMIZE RECOVERY HARDWARE

Before any hardware can be reused, it first must be successfully recovered. Retrieval should not impart any additional loads on the hardware. Approaches to hardware recovery have included barge landings, returning to land, and mid-air recovery. Although water retrieval has been attempted, it is not recommended due to the adverse effect that salt water has on avionics, electronics, and structures. This

approach was abandoned due to the elevated cost associated with refurbishing salt water damaged components [20]. By avoiding water retrieval, the engines would avoid maintenance that would have resulted from the corrosive nature of the salt water and thereby expedite turnaround time [21] [20]. When considering recovery of reusable systems, salt water is much more severe than returning to land at the launch site [3].” To minimize the impact of water recovery of hardware, commercial companies are examining alternative retrieval methods. For instance, SpaceX is pursuing landing an RLV on a barge at sea and Blue Origin is considering mid-air retrieval of the engines.

Reusable hardware is inherently heavier than its expendable counterpart because it has to be designed for multiple flights and endure harsh reentry loads. Every pound associated with recovery reduces payload capacity. As noted by Wertz, “recovery systems represent dead weight during launch [5].” Just as RLVs carry additional weight for recovery, airplanes carry additional weight for having the ability to land [22]. Unfortunately, this phenomenon is difficult to overcome and can be addressed as a “necessary evil” for recoverable hardware. As noted earlier, to survive the adverse conditions of reentry, the engines must be more robust to endure repeated subjection to mechanical stresses and thermal loads. This, in turn, necessitates higher safety margins to maintain an acceptable level of reliability and quality after each flight [8]. These added features for reuse result in a weight penalty for the engines. Table 1 shows the weight burden for incorporating reusability.

Reusable Feature	Penalty (approx. - % of Return Weight)
Reentry Heat Protection Integral or separate shield	10
Deorbit Propulsion and Propellants Much lower thrust than ascent	3
Descent Deceleration Aero surfaces and/or propulsion with propellants	15
Landing Systems Landing gear, aero surfaces and/or parachutes	10
Rapid Servicing Access doors, removable components, Health Management System	2
Lower Stress Levels	5

Table 1: Weight Penalty for Reusability [3]

6. LONGER SERVICE LIFE

Components with increased operating life require less maintenance, which decreases turnaround time and has a positive effect on operability. Therefore, attention should be paid to areas where improvements would provide the largest gains in safety, reliability, cost etc. to the system. This implies that components and/or systems that require frequent maintenance should be the focus of improvement strategies. Examining the failure rate of SSME components shows that the high pressure fuel turbopump (HPFTP) had the highest failure rate of all components followed by the high pressure oxidizer turbopump (HPOTP), large throat main combustion chamber (LTMCC), and the nozzle, as seen in Figure 1 [23].

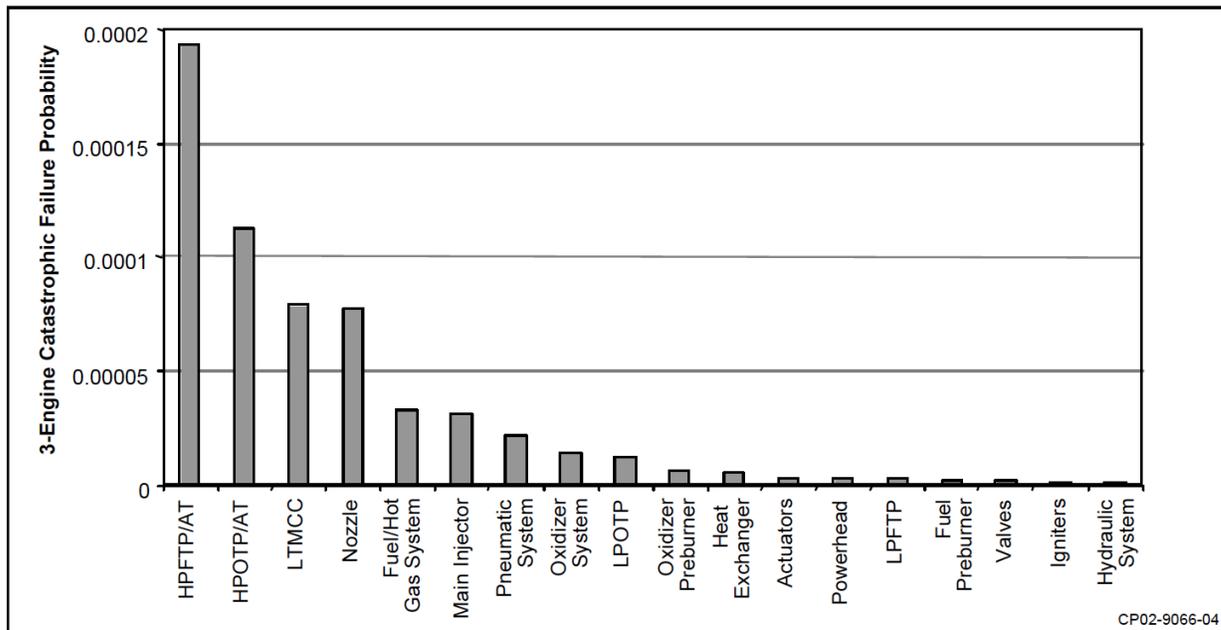


Figure 1 – Reliability of SSME Components

By improving the reliability of components with the highest failure rate (such as the HPFTP) rather than the igniters (with nearly zero failure rate), the greatest positive impact on the system would be realized. For example, turbomachinery is one of the leading causes for maintenance in the SSME [6]. Turbomachinery having a tendency towards repair is not limited to just rocket engines. Apparently, the Mean Time Between Repair (MTBR) for jet engines and power plants is also driven by turbomachinery [4]. Turbomachinery is very complex and operates under extreme conditions. Addressing ways to mitigate maintenance on the turbopumps would be a major breakthrough for reusability.

Increasing the inherent supportability and operability by actively designing in safety, reliability, maintainability, and reusability is another method employed to lengthen component life “rather than the traditional approach of designing for performance first and then “inspecting in” the operational effectiveness and operating cost attributes” [6]. Based on past history for reusable launch vehicles with a sample size of one, performance driven designs result in complex systems that are difficult to maintain. The SSME only operated for 8.5 minutes, yet required two months of maintenance after every flight. As alluded to by Weegar, “systems with useful life and reliability measured in seconds and maintainability and downtime are measured in days and month result in low availability and high launch operation cost; when the life and reliability are measured in hours and days and maintainability and downtime is measured in minutes and hours, the result high availability and low launch operations” which leads to operational effectiveness [6].

Derating or overdesigning the engine then operating at nominal is another way to increase service life and inherent reliability [23]. By operating at a lower power level, the components experience less mechanical, electrical, and thermal stresses [24]. This method for adding margin to the design produces a more robust engine by creating a less severe operating environment. This Increased reliability and useful life results in less maintenance activities. The combination of downgraded operation, higher reliability and increased design life leads to lower development costs because fewer engine qualification firings are required [25]. Aircraft reliability has matured to a point where flight maintenance is no longer

required [6]. As continued incremental changes are made to rocket engines and other reusable flight hardware, it is believed that RLVs will achieve the engineering confidence needed to mimic the aircraft industry and eliminate between launch maintenance.

7. EVOLUTIONARY RATHER THAN REVOLUTIONARY

As reusability is pursued, the designs should evolve from existing designs to limit the unknown. As noted by Taylor, "using an evolutionary design minimizes the development unknowns that could result in a launch failure [26]." Over the 30-year plus life span of the Space Transportation System both the SSME and SRB designs evolved. Not only was the flight hardware modified, but processes and procedures were updated. Based on post-flight analysis of the SRBs, design issues were corrected and reliability improved [27]. Likewise, the SSME design evolved with the incorporation of small incremental changes and more extensive modifications through several block upgrades [14]. The maturation of the SSME (through inspection, analysis, test, and multiple flights) has allowed it to achieve a reliability of 0.998 [28]. For the SSME, the first and only reusable rocket engine, to attain this reliability is impressive when compared to jet engines with heritage that spans more than 100 years [13] [24]. Since the SSME has accumulated over a million seconds of hotfire time, its rich history can be used to evolve the next generation of engines, much like the aircraft industry. As mentioned earlier, the aircraft industry has used its extensive years of experience to improve its designs and increase reliability. Likewise, the SSME's evolution over 40 years can serve as the point of departure for the next generation of rocket engines, especially in the pursuit of reusability. As material properties, processes, and analysis continue to improve, the incorporation of these advances can only enhance reusability. These materials can increase the useful service life of components with higher failure rates, like turbomachinery and MCC [29]. In the future, advance manufacturing techniques may prove to be beneficial to reusable systems. The incorporation of these techniques enables complex shapes to be produced without welds and mechanical fasteners, thus reducing part count and potential failure. This bottom line is that carefully considering materials can lead to engine life extension and less routine maintenance.

CONCLUSIONS

In conclusion, this paper presents several areas of concern for space flight hardware reusability. The first area is the definition of reusability, especially as it relates to rocket engines. The next concern is the set of roadblocks that impede the progress of developing and/or maturing reusable systems such as the absence of standards for reuse. The final factors discussed are operability and accessibility, which are crucial for the successful implementation of reusability. The next step is to develop the method for accessing the reusability of space flight hardware.

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