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REUSABILITY ASPECTS FOR SPACE TRANSPORTATION ROCKET ENGINES: PROGRAMMATIC STATUS AND OUTLOOK

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ABSTRACT

Rocket propulsion systems belong to the most critical subsystems of a space launch vehicle, being illustrated in this paper by comparing different types of transportation systems. The aspect of reusability is firstly discussed for the Space Shuttle Main Engine (SSME), the only rocket engine in the world that has demonstrated multiple reuses. Initial projections are contrasted against final reusability achievements summarizing three decades of operating this Space Shuttle engine. The discussion is then extended to engines employed on expendable launch vehicles with an operational life requirement typically specifying structural integrities up to 20 cycles (start-ups) and an accumulated burning time of about 6000 sec (Vulcain engine family). Today, this life potential substantially exceeds the duty cycle of an expendable engine. It is actually exploited only during the development and qualification phase of an engine when system reliability is demonstrated on ground test facilities with a reduced number of hardware sets that are subjected to an extended number of test cycles and operation time. The paper will finally evaluate on the logic and effort necessary to qualify a reusable engine for a required reliability and put this result in context of possible cost savings realized from reuse operations over a time span of 25 years.

1. INTRODUCTION

Reusability aspects for rocket engines used in today's launch vehicles are addressed, first by discussing reliability figures of different transportation systems including air- and space transportation, and by identifying the most critical subsystems that drive overall system reliability. Taking a brief look at the only existing, truly reusable engine today, the Space Shuttle Main Engine (SSME), one will notice that in over 25 years operation time until today (status August 2010), 132 Space Shuttle missions (equivalent to 396 engine flights) were served by a total number of 51 engines. Though initially designed for 55 missions, these operational figures demonstrate that the SSME has been reused on the average only eight times even though a small number of 11 candidates were able to exceed ten reuses in practice.[1] In this context it remains important to recall that after every Space Shuttle mission the effort necessary for post-flight service and maintenance of all three SSME engines was about equivalent to the production cost of half a new engine.[2]

The feasibility of reusable systems is further investigated and discussed by expanding the view on rocket engines for expendable launch vehicles, with operational life requirement typically specifying structural integrities up to 20 cycles (start-ups) and an accumulated burning time of about 6000 sec. Today, this life potential substantially exceeds the duty cycle of an expendable engine. It is actually exploited only during the development and qualification phase of an engine, when system reliability is demonstrated on ground test stands for extended number of cycles and operation time.

The paper finally evaluates the logic and effort necessary to qualify a liquid rocket engine for a required reliability and put this result in context of possible savings realized from reuse operations.

[1] These statements are derived from Space Shuttle flight chronology and employed engines' serial numbers
[2] According to information provided on www.nasaproblems.com

2. COMPARISON OF RELIABILITY FIGURES FOR VARIOUS TRANSPORTATION SYSTEMS

Prior to the discussion on reusability aspects for rocket propulsion, it is worthwhile to recall the extreme operational conditions experienced with space transportation systems. Typical performance values are given in Figure 2.1. The ratio of engine performance vs. engine mass, i.e. the specific power loading, may be used as a key figure to illustrate the extreme operational conditions for the different energy conversion machines.

The extreme operational conditions experienced with rocket propulsion are also reflected by the (demonstrated) mission reliability values for the different transportation systems. By focusing only air - and space transportation, Figure 2.2 compares the reliability values for these systems. For enabling a fair comparison, given values only account for catastrophic failures being characterized by the loss of vehicle and mission / payload. It is worthwhile to be mentioned that the demonstrated reliability for space launch vehicles are dominated by the Russian Soyuz family with more than 1700 launches. For the European Ariane family, the Ariane 4 launch vehicle has demonstrated a system reliability of 97,4%, through 116 launches with three catastrophic failures.[3] Today's European operational system Ariane 5 has accumulated so far 96%, through 52 launches with two catastrophic failures.[4] The US Space Shuttle has faced two catastrophic failures,[5] and will have demonstrated a reliability of 98,5% following its retirement after flight STS-134 in early 2011.

A significant difference does exist in terms of demonstrated system reliability compared to other transportation systems, despite of the significant safety

[3] With the Ariane 4 launcher family, loss of mission occurred with flight V36, V63, and V70.
[4] With the Ariane 5 launcher family, loss of mission occurred with flight V501, and V517. A partial loss was encountered with flight V510, in where one satellite was lost due to its placement into a wrong transfer orbit. The second satellite "Artemis" was recovered by a salvage mission using its own chemical and electric propulsion system.
[5] Two Space Shuttles have been lost, the "Challenger" in 1986 during the launch phase, and the "Columbia" in 2003 during the de-orbiting phase.

	Ground transportation	Air transportation	Space transportation
	 Formula 1	 Boeing 747, with four General Electric CF 6 80 engine	 Space Shuttle, with three SSME engines
Engine performance (approximate values, for single engine)	625 kW	13000 kW = 13 MW (eq. to 250 kN thrust, at take-off)	5050000 kW = 5,1 GW (eq. to 2278 kN thrust)
Ratio of engine perfor-mance / engine mass	7 kW / kg	3 kW / kg	1430 kW / kg

Figure 2.1: Engine performance characteristics of ground -, air -, and space transportation.

Space Launch Vehicles	Commercial Jet Airliners	General Aviation
		
91,7 %	99,99983 %	99,998 %
Western and Eastern launch vehicles analyzed, with 4038 cumulated launches, with 366 catastrophic failures (loss of vehicle)	Evaluated for aircraft manufactured in western world with MTOW > 30 tons: 745 loss of vehicle (1959 – 2005), with 444 million commercial departures	2001 US Figures: 349 loss of vehicles, with 25,4 million flight hours, assumed average flight time 1,5 h / flight
Data source: Astrium Space Transportation Data Base (launch data until 2003)	Data source: Boeing, "Statistical Summary of Commercial Jet Airplane Accidents, Worldwide operations 1959 - 2005", May 2006	Data source: NTSB Review of Aircraft Accident Data, NTSB/ARG-06/01, "U.S. General Aviation, Calendar Year 2001"

Figure 2.2: Demonstrated (mission) reliability figures for air- and space transportation systems.

effort undertaken also for space transportation systems. This may serve also as an indication for the extreme operational conditions to which the space transportation system and its subsystem are exposed to.

Figure 2.3 takes a closer look into the different subsystems for space transportation systems and general aviation that have been identified as the root cause for triggering catastrophic events. It is noted that only technical problems have been considered here, i.e. failures triggered by human errors have been excluded. Despite the fact that individual subsystems are strongly different for air- and space transportation propulsion systems, which actually limits a direct comparison, a significant difference may though be observed:

– For space transportation vehicles, propulsion is by far the most unreliable subsystem, being the origin for approximately 60% of all catastrophic events.

– For complex general aviation aircrafts, propulsion is one of the most reliable subsystem, contributing with only 0,07% to catastrophic events.

These figures are certainly driven by the fact that a major failure in the main propulsion system of a space transportation vehicle will inevitably lead to a loss of mission and thus vehicle due to very limited redundancies implemented. For air transportation system, a loss of engine power does not automatically result in a loss of vehicle, as winged vehicles can provide for a safe return

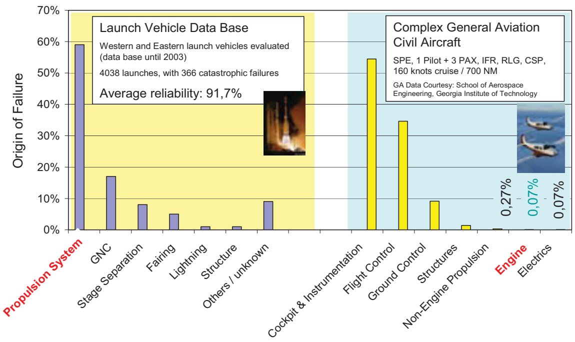

Figure 2.3: Vehicle subsystem origin of failure triggering catastrophic event.

to ground pending on available infrastructure being in reach.

Nonetheless, this rather simple comparison puts the "popular science" like idea of marketing the development of a space transportation system in a similar fashion as that of an "airliner-type" of transportation system strongly into question.

The extensive data base established with all build and tested SSME's, see also Section 3, does allow to take a closer look into the criticality of engine subsystems. Ref. [1] includes information on a Shuttle 3-engine catastrophic failure probability. This information is processed in Figure 2.4, showing that the subsystems being most critical in terms of triggering a 3-engine catastrophic event are:

– the high pressure fuel turbopump HPFTP,
– the high pressure oxidizer turbopump HPOTP, and
– the thrust chamber assembly TCA, including the main injector, the main combustion chamber (LTMCC), and the nozzle extension.

These components are exposed in operation to extreme thermo-mechanical load situations. Two major degradations may be identified here, limiting the safe life operation of these components and thus of a rocket engine:

1. low-cycle fatigue damage related mainly to an engine start-up and shut down operation, and
2. time-dependent damage driven by creep and material wear-out related to the duration of the engine main stage operation.

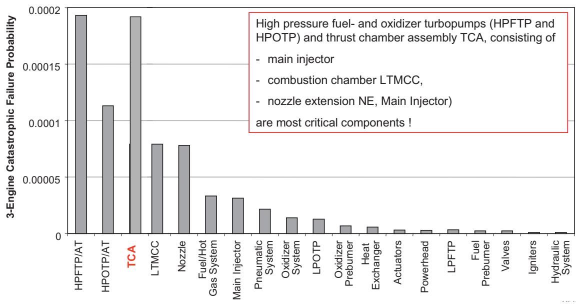

Figure 2.4: Engine subsystem origin of failure triggering catastrophic event.

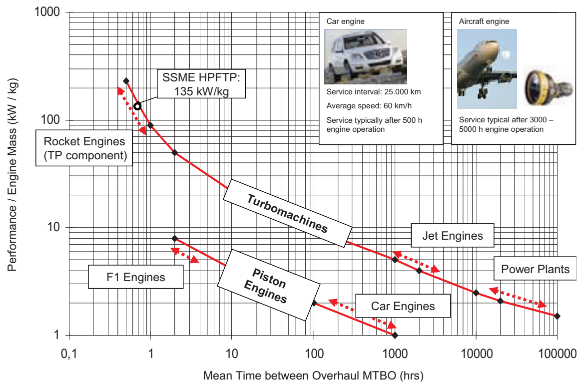

Figure 2.5: Mean time between overhaul for different classes of power machines.

For a further discussion on thermo-mechanical loads occurring during rocket engine operation, the interested reader is referred to the literature, e.g. Ref. [2], [3]. As example, Figure 2.5 addresses typical mean time between overhauls for different types of power machines, including piston engines and turbomachines. For comprehension, the SSME HPFTP is included, illustrating again the extreme operational conditions for rocket engines and its subsystem compared to other power machines. It is concluded that rocket engines and its subsystems work at the limits of feasibility in order to meet technical requirements, thereby still fulfilling defined rules for design robustness and safety.

Due to the rather extreme operational conditions prevailing in rocket engines, principle diverging requirements must be properly balanced at a very early stage in development, comprising among others engine performance, engine life, and development cost. Past and presence experience encountered worldwide with rocket engine development has shown that

– high performance (by exploring the limits) will result in high development cost and limited life (respectively reuse);
– low development cost will demand for a robust design approach but will only be achievable with reduced performance and limited life;
– enhanced operational life (in view of reusability) will demand performance to remain de-rated, but still result in significant development costs driven by an extended qualification effort related to the cost of engine testing.

These conflicting tendencies are regarded as a true dilemma for system engineering within an engine's development phase. Profound company heritage and well experienced engineers are one key element to guarantee a successful development.

3. SPACE SHUTTLE MAIN ENGINE - EVALUATION OF DEMONSTRATED REUSABILITY

Any discussion about reusable space transportation should be based on the demonstrated experience with the only one system of this kind in operation, the Space Shuttle. Entering into service in April 1981, 134 missions will have been conducted by beginning of 2011 when the remaining three orbiters "Atlantis", "Discovery", and "Endeavour" will finally be retired after almost 30 years of operation. This means that the Space Shuttles will have accomplished on average some 4,5 flights per year being launched every 2,5 months. As there were five orbiters initially existing to serve this transportation need, less than 30 flights would have been accumulated on each Space Shuttle in case of equal balance of missions. As known, two orbiters were lost in the course of tragic occurrences, the "Challenger" in 1986 during an ascent failure of a booster case sealing, and the "Columbia" in 2003 during the atmospheric reentry phase as a consequence of damages of its thermal protection structure. These and other circumstances enabled "Discovery" to accumulate 39 missions, clearly more flights than any other orbiter.

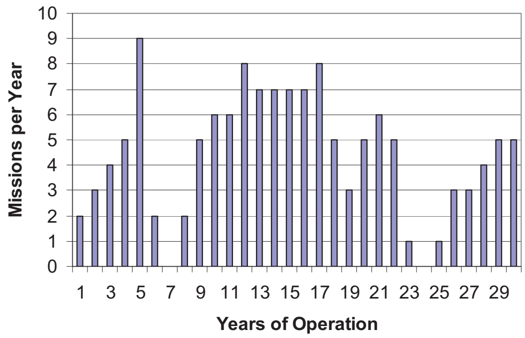

Figure 3.1: Space Shuttle flight rate distribution versus years of operation (Yr1=1981; Yr30=2010).

Though these numbers of reusability are today unmatched by any other space transportation system around the world, they also demonstrate that the whole Space Shuttle fleet finally remained far below its original design life of 100 missions to be performed in ten years, a time span that was later extended. Figure 3.1 shows the distribution of Space Shuttle missions per year from 1981 to 2010, highlighting that a maximum of nine flights was achieved only once in 1985. In the period between 1990 and 1997, an average number of seven missions per year could be sustained, which however, was never reached again in the years to follow.

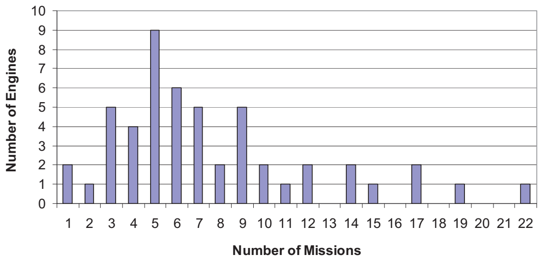

Figure 3.2: Number of SSME engines versus number of accomplished missions.

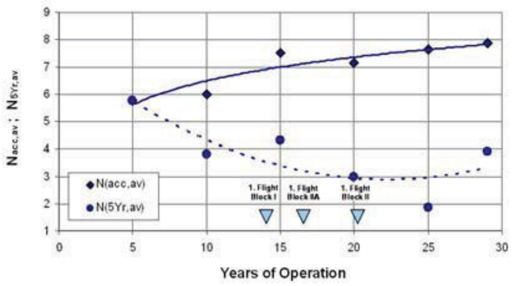

Figure 3.3: Evolution of average number of engine flights accumulated over time ($N_{acc,av}$) and average number of engine flights achieved within incremental five year time spans ($N_{5Yr,av}$).

As addressed in the Chapter 2, the overall reusability of this human rated space transportation system is largely determined by the reusability of its propulsion system and in particular, the reusability of the SSME. Since each orbiter is powered by three SSME's, 402 engine flights will finally fill the record of all 134 shuttle missions. According to flight chronology data, 51 engines (by serial numbers) will have served to accomplish this goal. These operational figures demonstrate that on an average basis, each engine has been used about eight times. A closer look reveals that in practice a small number of ten engines were actually able to reach ten and more reuses (note that one reuse is equal to two flights). Figure 3.2 depicts the number of SSME engines versus the number of accomplished missions. It can be seen that the number peaks at five missions with nine engines; one engine, e.g. the so-called mission leader (SN-2012) has actually been used 22 times.

At this point it should be recalled that the SSME was originally designed for an operational life of 55 flights which is equivalent to 27000 seconds. However, during operation this life potential was only exploited to 15% (i.e. approximately 8 out of 55) on an average scheme, and to 40% (i.e. 22 out of 55) by the fleet leader (SN-2012). This highlights that in practice engine maintenance turned out to be much more extensive than initially anticipated. An example for this is that only the very first five Space Shuttle missions ("Columbia": STS-1 to STS-5) were flown without a complete post-flight removal of all three SSME's (SN-2005, SN-2006, SN-2007). None of these three FMOF (First Manned Orbital Flight) Phase engines ever returned to flight. In contrast to this, the fleet leader engine (SN-2012) was first flown on STS-6 (Pos. 3; "Challenger") in April 1983 and last on STS-93 (Pos. 1; "Columbia") in July 1999, 16 years later.

Figure 3.3 contrasts the evolution of the average number of engine flights accumulated over time ($N_{acc,av}$) from the evolution of the average number of engine flights achieved within incremental five years time spans ($N_{5Yr,av}$). The figure is interesting for two aspects. Firstly, it shows that the average number of engine flights within the first ten years of operation reached a number not higher than $N_{acc,av}$~ 6. In the course of the different engine upgrades, i.e. Block I, Block IIA, and Block II (being discussed in Ref. [4] in more details), this figure could stepwise be improved to the number of $N_{acc,av}$~ 7,9 finally achieved by 2010. Secondly, if one follows time span windows of five years, the average number of engine flights dropped stepwise down to a number of $N_{5Yr,av}$~ 3,8 within these periods of time. This means that each engine was finally going to be subjected to a mission only every 16 months. The reasons for this evolution are twofold:

– Firstly, the average number of missions the Space Shuttle was flying from 1998 onwards dropped down to a level of less than four flights per year;
– Secondly, more engines were successively available to serve this reduced number of missions.

The first flight of improved Block IIA SSME's took place on STS-89 ("Endeavour", SN-2043, -2044, 2045) in January 1998. Following this flight, engine SN-2043 was used on five more missions, while engine SN-2044 was used 13 more missions reaching the highest number of flights of all 16 engines in operation with follow-up serial numbers up to SN-2061 (last serial number employed on operation). These late 16 engines were used up today on 31 shuttle missions (93 engine flights) resulting in a reduced average number of flights towards Space Shuttle retirement of N_{av}~ 5,8. This number actually matches quite well the level of SSME reusability that was representative for the first ten years of Space Shuttle operation.

As reported in Ref. [1], the general evolution of the SSME durability, reliability and operability was largely linked to an extensive on ground test programme. In the course of the initial engine development and qualification phase, 726 tests were performed with an accumulated test time of 110253 seconds prior to STS-1 in April 1981. These numbers were increased to 2476 ground tests totaling 735074 hot fire seconds by 1996 (Ref. [1]), respectively 2929 ground tests totaling 972132 hot fire seconds by 2002 (Ref. [4]). It shows that a six-fold flight equivalent effort in test time was maintained on ground to back-up engine flights. Figure 3.4 compares these numbers. According to Ref. [1], this aggressive engine test program was able to demonstrate an engine reliability of 0,99927.

In practice, the SSME reusability demonstration program has been based on two elements, e.g. (1) ground test fleet leaders and (2) flight leaders. Flight leaders were established by successively employing a limited number of engines, taken from different upgrade phases, to an increasing number of Shuttle missions. In doing so, some engines like SN-2012 (22 flights), SN-2019 (19 flights), SN-2031 (17 flights) and their incorporated components were actually able to accumulate a comparatively high fraction of its design life, e.g. 40%, 35%, and 31% respectively, while a large number of other engines, e.g. 21, did not even reach 10% of it (note that this statement here is derived for the engine as a whole, not for each component, since individual components may have been exchanged in the course of each engine's life).

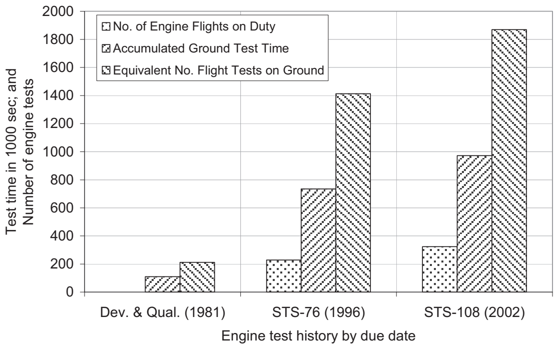

Figure 3.4: On-ground test history of SSME up to 2002.

Similar to flight leaders, ground test fleet leaders have been established for each component as well. Those fleet leaders are units that have achieved the highest time without a failure, respectively the lowest time to failure. Ref. [5] gives a brief summary on the status of fleet and flight leader components by the year 2001 (Block IIA Upgrade). The results confirm that the most critical engine components, i.e. the components that demonstrated lowest life, include the main combustion chamber LTMCC, as well as and the high pressure turbopumps HPOTP, and HPFTP. This information is in line with the data presented in Figure 2.4. Unfortunately, Ref. [5] does not give any information on how many engines are practically involved in the data on fleet and flight leader units.

4. LIFE CYCLE COST ASSESSMENT BASED ON TODAY'S UTILIZABILITY OF EXPENDABLE LIQUID ROCKET ENGINES

Any affordability assessment for expendable or reusable liquid rocket engine requires the estimation of the complete life cycle cost which usually includes

– the development cost,
– the production cost, and
– the operational cost.

One of the main input parameters for the development and production cost estimation is the life time capability of the technologies employed. Besides these technologies, the hot fire development and qualification test program is also a major development cost driver.

In addition, the safeguarding of engineering competences over the full production period until the start of a new successor development concludes the list of cost contributors. Therefore, these aspects will be highlighted in more detail in the following paragraphs.

<u>Engine Life Time Capability</u>

Engine life data for an expendable engine is generally obtained during the engine's development and qualification program. During such programs, a limited number of engine candidates and associated tests have to provide all the information needed to finally assess the reliability and safe life for each subsystem as well as for the engine as a whole. In Western Europe, engine life data is mainly based on the experience with the primary stage engines Vulcain 1 and Vulcain 2. Both engines are gas-generator cycle engines in the 1000 kN to 1350 kN thrust class using the cryogenic LOX/LH2 propellant combination. As primary stage engines of the Ariane 5 launcher, ascent burning times are typically around 540 seconds, well comparable to the burning time of the SSME on the Space Shuttle.

In the frame of a development program for an engine of the Vulcain type, up to 10 engines are typically employed for achieving final qualification. A total number of some 20 tests and more are being conducted to accumulate a test time of about 10000 seconds per engine. As addressed in Chapter 2, two major degradations limit the safe life operation of a rocket engine, the low-cycle fatigue damage related mainly to an engine start-up and shut down operation, and the time-dependent damage driven by creep and material wear-out related to the duration of the engine main stage operation. Concerning the main combustion chamber (MCC) of a rocket engine, which is typically one of the most critical subsystems in terms of life capability, one can approximately evaluate the relationship between cycles-to-failure and mission flight time as given in Figure 4.1. The figure shows that a primary stage engine with a mission operation time of about 550 seconds may be subjected to about 10 cycles without any major degradation. If this flight time decreases to 250 seconds, which is more representative for engine operation on a booster stage, the MCC-subsystem will approximately be able to accomplish 20 cycles. A further reduction of the engine's operation time to about 100 seconds would further enhance the number of cycles-to-failure to a level beyond 50 (note that this simplified consideration may be used only as a first order approximation).

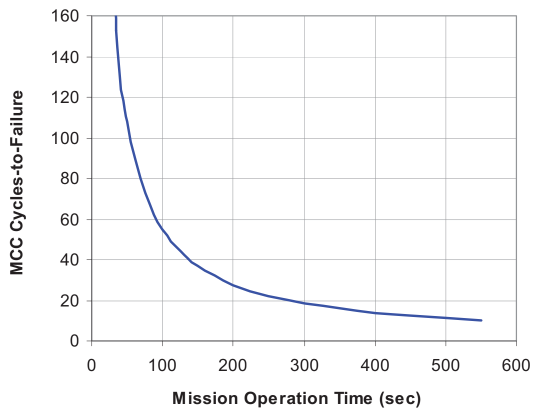

Figure 4.1: First order relationship between cycles-to-failure and mission operation time for the main combustion chamber of a liquid rocket engine.

Despite the potential of reaching 10, 20, or 50 cycles-to-failure depending on the engine's mission operation time as disclosed in Figure 4.1, an engine's safe life is always defined by employing a so-called margin of safety against this potential life capability. Assuming a factor of three for this margin of safety, a life potential of 20 cycles-to-failure (engine operation on a booster stage) will turn into about seven cycles for safe life only. Subtracting two more cycles for initial engine adjustment and acceptance, safe life is finally limited to using such an engine five times.

Scope and Effort of Engine Testing during Development

The scope and effort of engine testing is the main cost discriminator for the development cost of liquid rocket engines. Therefore, Table 4.1 compares the pre-flight test effort that was employed in the course of development and qualification for various liquid rocket engines. One can see that the total test effort invested is quite different in terms of pre-flight tests, number of engine prototypes, and the accumulated test time - but why?

One of the main reasons for the different approaches is the lack of an existing standard for development and qualification testing in the western hemisphere. Only two recommendations are published for new engine designs by comparing previous hot fire test programs, however without any obvious justification. The two recommendations are

– a test program should consist of 400 tests with 40000 seconds of accumulated firing spread over approximately 15 prototypes, see Ref. [6], or
– a minimum of 150 tests with 50000 seconds of accumulated firing should be performed, see Ref. [8].

In fact the two recommendations may be highly questionable by looking at the performed test programs as given in Table 4.1. In addition, a general statement about the test scope can be misleading because the liquid rocket engine utilization, i.e. booster, main stage or upper stage induces different mission requirements. Hence, a specific development strategy is needed for every liquid rocket engine development. In order to partially understand the different hot fire test programs, the applied strategies in past liquid rocket engine developments must be briefly recalled. These are based either on

– a formal reliability demonstration requirement
(i.e. test as long as the reliability level is demonstrated);
– a design verification specification (DVS) to reduce the number of prototypes, and
(i.e. test plans according to specific verification objectives);
– an objective based variable test/time definition to reduce the test scope.
(i.e. test including company heritage on component failure occurrence).

Examples for the different strategies include the development programs for the RD-0120 engine, subjected to a formal reliability demonstration requirement, and for the SSME using the design verification specification approach, and for the RS-68 introducing the objective based variable test/time definition, see Ref. [6], [7], and [10].

Further metrics were defined to quantitatively compare the different strategies: the ratio of design life over effective burning time, and the mission burning time over average test time. Table 4.2 includes the related information for the different rocket engine developments. It may be concluded that two principle test strategies have been established:

– A rather high value of approx. ten for *engine design life over effective burning time*, and an *average test time* similar to the *mission burning time*, as applied for European LOX/H2 Vulcain type engines and Russian LOX/Kerosene RD-170 & RD-180 type engines.
– A rather moderate value of four to five for *engine design life over effective burning time*, and an *average test time* significantly below *mission burning time* (factor 0,5 and less), as applied in the test strategies for diverse LOX/H2 US and Japanese engines, and the Russian RD-0120 engine.

But which strategy is to be preferred in practice? The historic review of actual flight failure occurrence observed on US liquid propelled launch vehicle provide further insight about the adequacy to test rather shorter durations instead of relying on extended or full mission duration

Engine	**Dim.**	**SSME**	**RS-68**	**LE-7**	**Vulcain 1**	**Vulcain 2** by 2002	**RD-0120**	**RD-170**	**RD-180**
Country		USA	USA	JPN	WEU	WEU	RUS	RUS	RUS
Cycle		FRSC	GG	SC	GG	GG	FRSC	ORSC	ORSC
Propellants		LOX/H2	LOX/H2	LOX/H2	LOX/H2	LOX/H2	LOX/H2	LOX/RP1	LOX/RP1
Vac. Thrust	[kN]	2280	3300	1080	1140	1350	1960	7900	4150
Vac. Specific Impulse	[s]	452,3	409	446,1	431,2	434	456	337	337,8
Mission Burning Time (BT)	[s]	520	250	350	600	540	460	145	190
Design Life (n_c ; BT_{tot})	[- ; s]	55 ; 27000	8 ; 1200	12 ; 1720	20 ; 6000	20 ; 5400	4 ; 2000	10 ; 1450	10 ; 1900
Engine Prototypes	[-]	20	12	14	16	6	90	71	12
Preflight Test Number	[-]	726	183	282	222	133	793	242	95
Accumulated Test Time	[s]	110253	18945	15639	78538	59497	163000	22400	15574
Years of Development	[Yr]	71 - 81	97 - 02	83 - 94	85 - 96	95 - 02	76 - 87	75 - 85	96 - 02

Table 4.1: Comparison of pre-flight testing effort employed in the course of development and qualification for different liquid rocket engines.

Engine	**Dim.**	**SSME**	**RS-68**	**LE-7**	**Vulcain 1**	**Vulcain 2** by 2002	**RD-0120**	**RD-170**	**RD-180**
Effect. Burning Time (EBT)	[s]	4160	250	350	600	540	460	145	190
Design Life (BT_{tot})	[s]	27000	1200	1720	6000	6000	2000	1450	1900
Average Test Time (ATT)	[s]	151,9	103,5	55,5	353,8	447,3	205,5	92,6	163,9
BT_{tot} / EBT	[-]	6,5	4,8	4,9	10,0	11,1	4,3	10,0	10,0
BT / ATT	[-]	3,4	2,4	6,3	1,7	1,2	2,2	1,6	1,2

Table 4.2: Comparison of pre-flight testing effort employed in the course of development and qualification for different liquid rocket engines (Note: EBT = n BT; effective burning time has been calculated with n = 8 as a mean average value of utilization for SSME, e.g. see Fig. 3.3, and n = 1 for expendable engines).

Main Program Requirements		ELV	RLV-5	RLV-10	RLV-15
Mission Number	[-]	1	5	10	15
Flight Mission Duration	[s]	250	250	250	250
Reliability Demonstration	[%]	98	98	98	98
Confidence Level	[%]	60	60	60	60
Refurbishment	[-]	n/a	No	No	No
Reliable Life	[s]	2400	2400	3800	5100

Table 4.3: Main Mission Requirement Assumptions for Affordability Assessment.

Engine Usability		ELV	RLV-5	RLV-10	RLV-15
Country		WEU	WEU	WEU	WEU
Engine Prototypes	[-]	10	23	31	37
Preflight Test Number	[-]	190	307	534	766
Accumulated Test Time	[s]	21000	48300	102300	162800
Average Test Time	[s]	110,5	157,3	191,6	212,5

Table 4.4: Test Scope Definition for Affordability Assessment.

tests. Historically, about 60 % of all observed liquid rocket engine failures with US launch vehicles in operation were experienced during ignition and start-up operation and the remaining 40 % were split into a 20/20 percent failure portion up to 200 seconds and 300 seconds, respectively. Figure 4.2 depicts this information, as included in Ref. [12].[6] Therefore, the need to test for long durations is a priori not justified and any related approach may in fact be less efficient in regard to achieving engine qualification and thus be questioned.

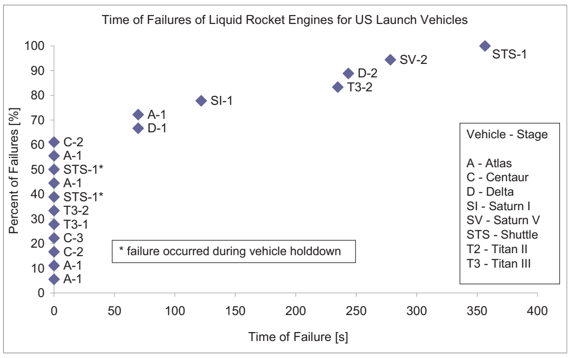

Figure 4.2: Abnormal engine shut-downs experienced with liquid rocket engines of US launch vehicles.

<u>LCC for Various Expendable and Reusable Engine Utilization Scenarios</u>

In the frame of generic life cycle cost (LCC) assessment, a more scientific based approach was developed for defining the scope and effort of four envisaged engine utilization scenarios:

1. ELV, i.e. the classical expandable engine utilization;
2. RLV-5, i.e. five engine flight missions, corresponding to four engine reuses;
3. RLV-10, i.e. ten engine flight missions, corresponding to nine engine reuses; and
4. RLV-15, i.e. 15 engine flight missions, corresponding to 14 engine reuses.

The analysis was generally built on a utilization of the corresponding liquid rocket engine within the limits of its safe life operation, without significant maintenance, resp. engine overhaul. The approach was designed to take into account the observed percentage of failure times and the proper weighting of tests which are shorter than full mission duration firings (note that this study was focused only on the affordability of the engine system as a function of its number of reuses, however not on the vehicle as a whole). The objective was to evaluate a suitable scope and effort for engine development testing in terms of number of hardware sets, number of hot fire tests, and total accumulated hot fire test time employing a mission equivalent binomial extended success-oriented testing model combining both modern reliability engineering techniques and parametric cost modeling, see also Ref. [13] for further details.

The main mission assumptions for the four engine utilization cases are given in Table 4.3. The resulting test program scope in terms of number of engine prototypes, number of preflight test number, accumulated test time, and average test time is given in Table 4.4.

The defined hot fire test scopes for the development and qualification phases for the four engine utilization scenarios are well comparable with the figures given in Table 4.1 and Table 4.2 but with one major difference, i.e. the number of prototypes. Except for the engines RD-0120 and RD-170, this number turns out to be higher mainly as a consequence of the formal reliability demonstration test strategy and the link with credible life time capabilities of the assumed technologies. However, modern reliability engineering techniques (Bayesian framework) promote a significant test scope reduction and hence also the needed number of prototypes when compared to classical Binomial reliability demonstration test programs, see e.g. Ref.[13]. This modern approach results in similar numbers of hardware sets needed for a formal reliability demonstration for the defined reuse level RLV-5 when compared to the DVS approach used for the SSME without significant maintenance in between flights (applicable to the Space Shuttle operation within the first five flights STS-1 to STS-5).

The particular engineering safeguarding aspects in the affordability assessment is covered by means of an operational concept scenario which takes into account the initial development, the activities defined for the engineering safeguarding in between two successive engine development programs, and the number of production units based on a constant yearly flight and

[6] It is noted that the information depicted in Figure 4.2, according to Ref. [12], includes engine shut-downs driven by sensor problems and other not pure engine hardware related events, such as engine / structure interaction. These are also named "engine failure", justified by the risk of mission loss associated with engine shut-down. This is justified by its impact on mission system reliability figures.

constant yearly production rate. The complete operational concept scenario was assumed to last 25 years for all four engine utilizations for ease of comparison.

Based on the defined operational concept scenario, the required engine numbers for the flight missions and engineering safeguarding activities can be derived which are 215 for ELV, 53 for RLV-5, 30 for RLV-10, and 23 for RLV-15, respectively. These production quantities were used as input parameter for the parametric price assessments.

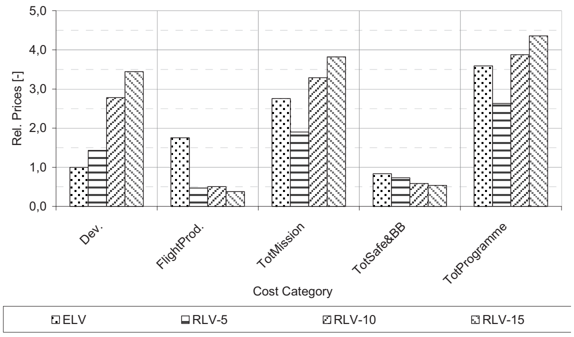

Figure 4.3: Affordability assessment including engineering safeguarding.

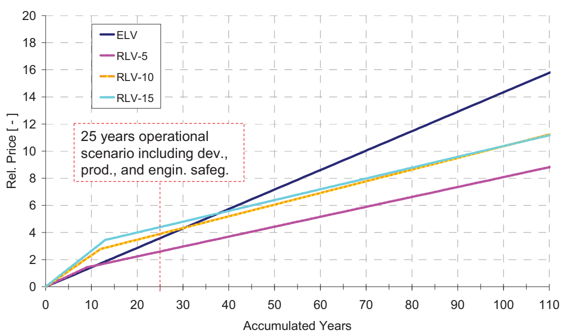

Figure 4.4: Total price versus accumulated years.

Finally, the parametric cost estimation software PRICE was used to estimate the development and production cost for the defined operational concept scenarios and the input parameters driving the development hot fire test scope which was modeled with a user defined cost model. The final relative price estimates for the development, production, and engineering safeguarding is shown in Figure 4.3. The figure depicts also the total mission cost (development + production) as well as the total cost for the mission and the engineering safeguarding affordability assessment.

Based on the performed affordability assessment, a significant price advantage is disclosed for utilization a liquid rocket engine within the limits of its safe life operation but without significant maintenance (e.g. without engine disassembly followed by substantial subsystem overhaul). The cost advantage mainly relates back to the development phase. Of course, the engine mission requirement is an important factor for safe life operation given today's technology, because an increase in the flight time from 250 seconds up to 550 seconds (i.e. burning time of a primary stage rather than that of a booster stage, see Figure 4.1) would erode the capability for engine reuses and thus approximate the costs as defined by the ELV-case. On the contrary, if actual mission operation time would be significantly reduced below 250 seconds (for instance suborbital flight of a space tourism vehicle), the RLV-5 case would shift to much higher reuse-numbers thus exploiting additional cost advantages in front of ELV as indicated within Figure 4.2.

5. CONCLUSION

The rocket propulsion system belongs to the most critical subsystem of a space transportation system. This is driven by the extreme operational load conditions to which the system is exposed during operation. This affects also the reusability aspect; its feasibility has principally been demonstrated by the SSME, although effective reusability finally achieved has been significantly lower than initially designed to. The most critical subsystems include the HPFTP, HPOTP, and the TCA.

Limited reuse capability has been demonstrated through engine development and qualification testing also with ELV engines such as Vulcain and Vulcain 2. The need for higher engine test times than mission duration is driven by the limited number of engine hardwares used for engine development and qualification. This heritage on limited engine reuse capability may be exploited within space launch missions - with the prerequisite of course that the launcher is also designed for reusability.

Cost assessment shows that - from engine perspective - limited reuse for booster type engines up five missions is most interesting. This is principally achievable with today's technology, as typically demonstrated through engine development and qualification programs. Key life cycle cost assumption here is that within this five missions operation no major engine overhaul is needed.

It is stressed that the conclusive discussion on reusability must be based on an integrated reusable vehicle concept. The vehicle maintenance and refurbishment concept must be harmonized with the propulsion system. Pending on the vehicle concept and operation, some conclusion addressed in this paper may be different if the life cycle cost assessment is performed at vehicle level.

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7. ABBREVIATIONS

Acc - Accumulated
ATT - Average Test Time
Av - Average
BT - Mission Burning Time
EBT - Effective Burning Time (EBT = n•BT)
DVS - Design Verification Specification
ELV - Expendable Launch Vehicle
FRSC - Fuel-Rich Staged Combustion Cycle
GG - Gas Generator Cycle
H2 - Hydrogen

HPFTP	- High Pressure Fuel Turbopump
HPOTP	- High Pressure Oxidizer Turbopump
JPN	- Japan
LCC	- Life Cycle Costs
LOX	- Liquid Oxygen
LTMCC	- Large Throat Main Combustion Chamber
MTOW	- Maximum Take-Off Weight
MCC	- Main Combustion Chamber
n	- Number of engine utilizations (missions)
ORSC	- Oxidizer-Rich Staged Combustion Cycle
RLV	- Reusable Launch Vehicle
RP1	- Rocket Propellant -1 / Kerosene
RUS	- Russia
SC	- Staged Combustion Cycle
SN	- Serial Number
STS	- Space Transportation System
SSME	- Space Shuttle Main Engine
TCA	- Thrust Chamber Assembly
TMD	- Total Mission Duration
TP	-Turbopump
US	- United States
Vac	- Vacuum
WEU	- Western Europe
Yr	- Year

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