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A Series of Unforeseen Events:
The Space Shuttle, Mission Evolution, and Flexibility

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A common objective in the design of a new space system is that of flexibility, or the capability to easily modify that system in the future in response to a changing environment or changing requirements. The focus of this paper is a case study of the U.S. Space Shuttle to glean some insight into fundamental characteristics of flexibility in human space systems and how this may be applied to future systems. Data is presented on the evolution of mission requirements over time for 120 missions performed by the Space Shuttle over a period of approximately 27 years. Distinct trends in the time domain – as well causes of these trends – are identified, and early manifest plans from 1982 serve as a confirmation that these trends were not originally anticipated. Eight examples are then presented of engineering modifications that allowed the Shuttle to adapt and accommodate these requirement changes. Conclusions are drawn on the nature of flexibility as experienced by the Space Shuttle. Finally, remaining questions are posed regarding how flexibility is considered in the initial stages of design for space systems.

Nomenclature

EDO = Extended Duration Orbiter
FY = Fiscal Year
ISS = International Space Station
NASA = National Aeronautics and Space Administration
OBSS = Orbiter Boom Sensor System
ODS = Orbiter Docking System
RMS = Remote Manipulator System
SRB = Solid Rocket Booster
SSPTS = Station-Shuttle Power Transfer System

I. Introduction

ONE common objective in the design of a new space system is that of flexibility, or the capability to easily modify that system in the future in response to a changing environment or changing requirements. The body of research on this topic has been growing, but there is still much to be completed in terms of developing consistent metrics for characterizing and quantifying a system's flexibility, and trading that flexibility against other performance metrics or resources. The focus of this paper is a case study of the U.S. Space Shuttle to glean insight into basic characteristics of flexibility in human space systems and how this may be applied to future systems.

As this paper will show, the Space Shuttle is an outstanding example of a system with a history of changing requirements. On January 5, 1972, President Richard Nixon announced the approval of the Space Transportation System, or Space Shuttle, a system which would provide, according to NASA Administrator James Fletcher, "the means of getting men and equipment to and from space routinely, on a moment's notice if necessary, and at a small fraction of today's cost." Further, this would be accomplished "within the framework of a useful total space program of science, exploration, and applications."[1] NASA's challenge following Nixon's announcement became one of transforming an expansive vision for the Shuttle into a practical reality under a highly constrained development budget. While the Shuttle never lived up to the cost and flight rates that were promised at the

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program's inception, it is notable that the design decisions made in the 1970s produced a system which even today is, arguably, unsurpassed in the variety of capabilities which can be fulfilled with a single space vehicle. With relatively few architectural modifications, the Shuttle has accommodated satellite deployment, satellite retrieval and servicing, launch of interplanetary robotic probes, classified Department of Defense missions, space station logistics and assembly flights, and a wide variety of science and engineering research missions. By the time of its planned retirement in 2010, the Shuttle will have endured and responded to nearly three decades of changes in requirements and environments. Many of these changes emphasized or deemphasized different types of missions at different times in the Shuttle's life. While the Shuttle may not be the "optimal" flexible space system, it has adapted to substantially changing requirements and environments with fair success and is deserving of attention.

It is important here to note the distinction between flexibility and robustness. Both terms refer to the ability of a system to handle change, typically after it is fielded. However, unlike robustness, flexibility implies that in the presence of requirement or environment changes, a user can exercise options to adapt the system. These adaptations can result in improving a performance metric in a given scenario or altogether changing system functionality. Thus, in the example of the Space Shuttle, an examination of either robustness or flexibility would require an answer to the question of "Did requirements change?". In the context of flexibility, however, a question that must also be asked is "What actions or modifications did the user make in order to adapt to that change, and how effective were they?". Conceptually, the ideal flexible system is one for which a minimal change to the system itself enables a large change in functionality or performance. In the pages that follow, the first question is analyzed quantitatively, and the second is analyzed qualitatively.

II. Evolution of Space Shuttle Mission Requirements

Presented next is a primarily quantitative analysis of the history of the Space Shuttle program in the context of the evolution of mission objectives. Data on launch dates, crew, duration, final orbit, and payloads are collected from three principal sources,[2,3,4] and the most important step is the classification of each mission into one of the five categories described below. While in some cases a given mission will have elements common to two or more categories (for example, almost every Shuttle mission includes some science), the authors' judgement was used to classify missions in terms of their prime objectives. For transparency, Tables 1 and 2 include the mission classifications for each Shuttle mission considered.

1. **Test Flights** include the first four Shuttle flights (STS-1 through STS-4), considered the Orbital Flight Test Program. These four flights are unique in the Shuttle program history in that they carried only two crew (with ejection seats) and were not considered operational flights.[5]
2. **Dedicated Defense Flights** are flights dedicated to flying missions specified by the Department of Defense. Most of these ten missions have orbits and payloads which have been deemed classified.
3. **Space Station Flights** are flights involving rendezvous with an inhabitable orbiting facility (*Mir* or the International Space Station).
4. **Unmanned Spacecraft Servicing Flights** include flights with a primary mission involving the deployment, retrieval, or servicing of a free-flying unmanned spacecraft which has an intended mission life longer than that of a Shuttle mission. Many of these flights are deployments of satellites (i.e. in which the Shuttle is used in lieu of an expendable launch vehicle). Also included in this category are servicing missions to the Hubble Space Telescope and deployments of the *Magellan*, *Galileo*, and *Ulysses* interplanetary spacecraft.
5. **Dedicated Research Flights** are flights which focus on science or engineering research, typically for extended durations. Included in this category are flights of the Spacelab module and any flights with specialized astronomical, remote sensing, or other science or engineering payloads.

A. Achieved Missions

Table 1 shows basic mission data for each of the 120 Shuttle missions flown through January 2008, and this data is shown graphically in terms of primary mission in Figures 1-3. Figure 1 depicts each of the 120 Shuttle missions separately as yellow circles placed at their respective launch dates but decomposed in the vertical dimension by mission type. It is easily seen from Figure 1 alone that there is distinct "clumping" of Shuttle missions in each mission category during certain ranges of time. This clumping is brought into focus in the *y*-axis of Figure 2, which shows the dominant mission types by percent of missions flown in three-year periods spanning from 1981 through the end of 2007. It becomes clear from these figures that definite changes in mission requirements have occurred over the Shuttle's 27-year history, specifically in terms of three major mission categories. In 1984-1986, unmanned spacecraft servicing accounted for 69% of Shuttle missions, but by 1993-1995, almost the same percentage (67%) was attributed to dedicated research flights. In 1999-2001, 79% of flights were to an orbiting space station, and in 2005-2007 that number increased to 100%.

It is important to note that each of these three spikes in mission type frequencies can be explained to a large extent by specific events driving decisions within the Space Shuttle program. For example, the *Challenger* disaster prompted presidential action to limit commercial communications satellite use of the Space Shuttle to only payloads with national security or foreign policy implications. The *Challenger* disaster also prompted many Department of Defense satellites to be launched on expendable launch vehicles instead of the Shuttle (including 20 Global Positioning System satellites).[5] This explains the decline in both unmanned spacecraft servicing and defense flights after 1986. Also, the start of space station flights (first to *Mir* and then to the International Space Station) in the mid-1990s is tied to the maturation of plans for a space station and especially the invitation extended to Russia in late 1993 to join the international partners.[6] Finally, the *Columbia* disaster in 2003 was a third major event which served as a catalyst for a new vision for the nation's space program which would retire the Shuttle in 2010 after fulfilling its commitments to International Space Station (ISS) assembly. As a result, every flight in 2005-2007 was destined for the ISS.

Interestingly, Figure 3 adds that over its history, not only has the Shuttle experienced three distinct periods of specific mission type predominance, but the dominant mission types in these periods have occurred in almost equal numbers. That is, 31% of Shuttle flights have been to service unmanned spacecraft, 30% have been dedicated to research, and 28% have been destined for a space station. Overall, it is rather remarkable that the system was able to accommodate these changes in mission type, especially given the consequences of not doing so. Additionally, the next section will illustrate the disparity between the planned and actual Shuttle manifests, suggesting the unexpected nature of these changes in mission type.

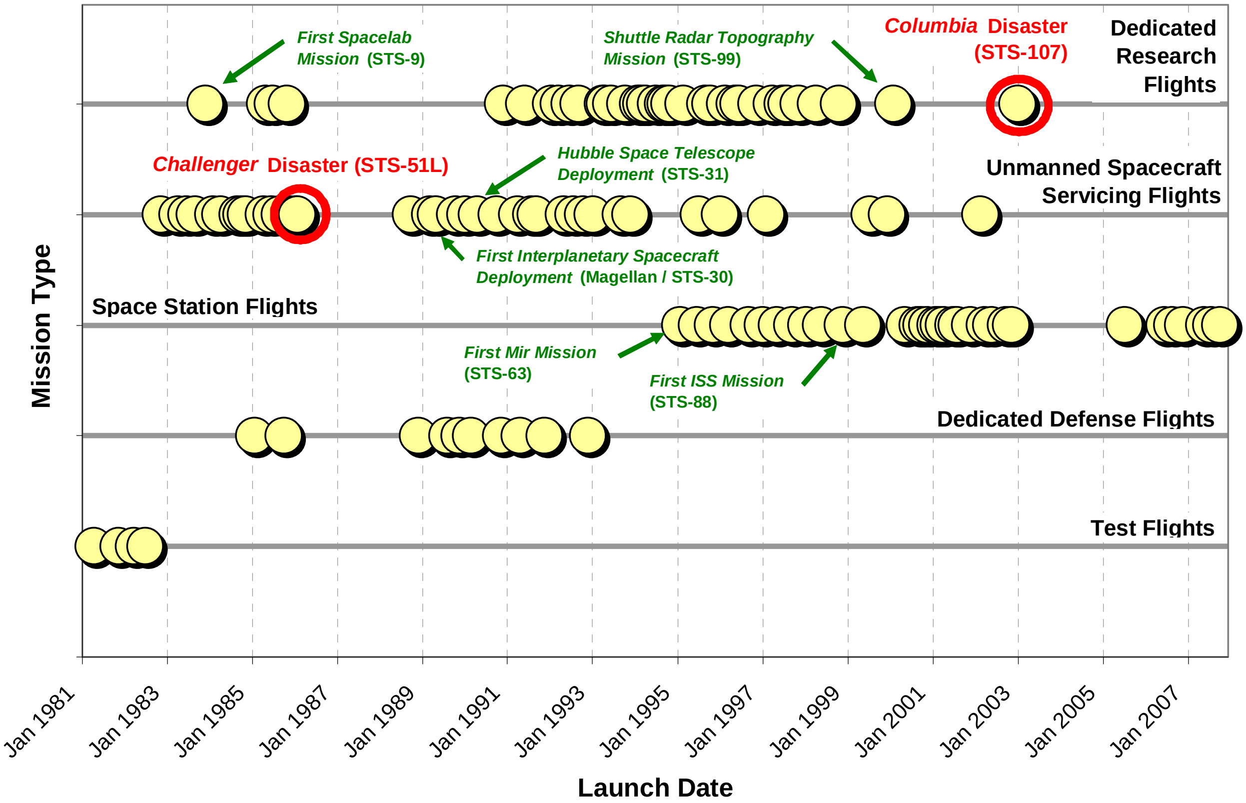

Figure 1. Event-centric representation of Shuttle missions through Jan. 2008.
Each horizontal line represents one mission type, and each yellow circle represnts one Shuttle mission. Selected milestone missions are labeled for reference.

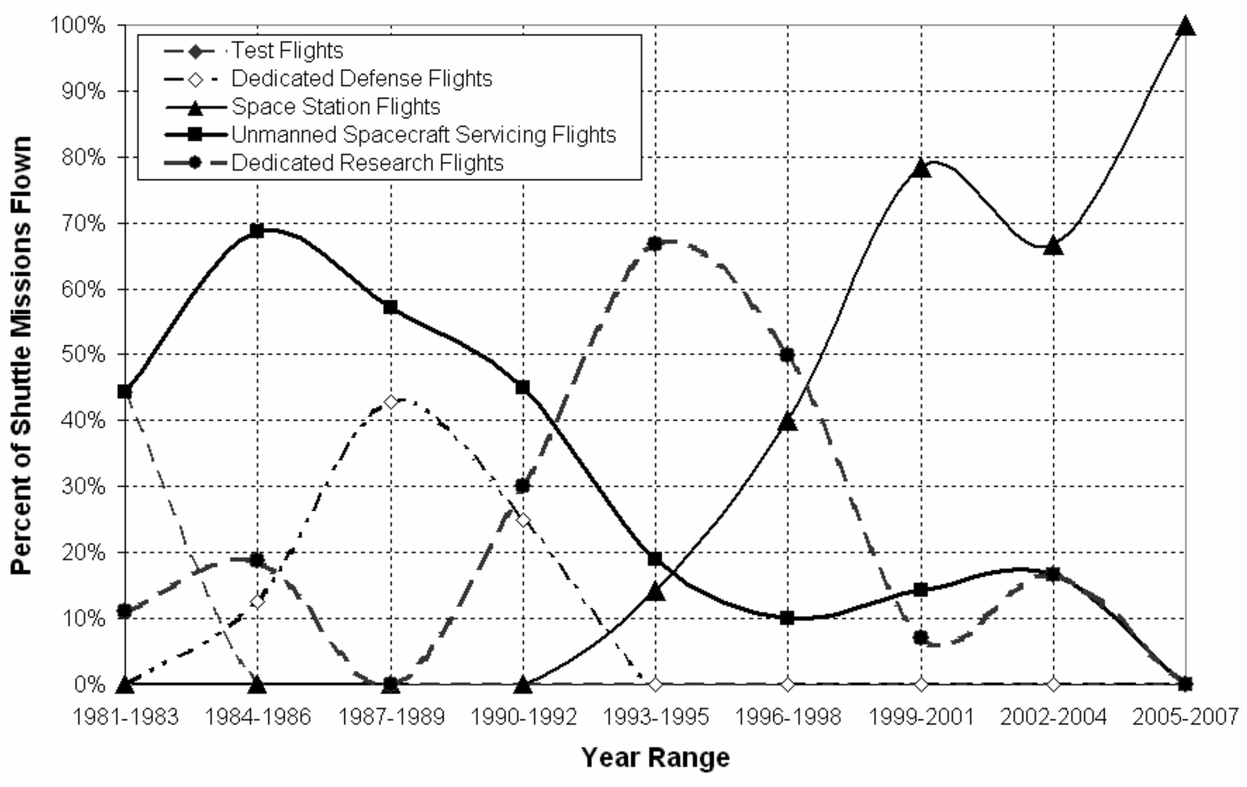

Figure 2. Time-History of Space Shuttle Usage by Primary Mission Type.

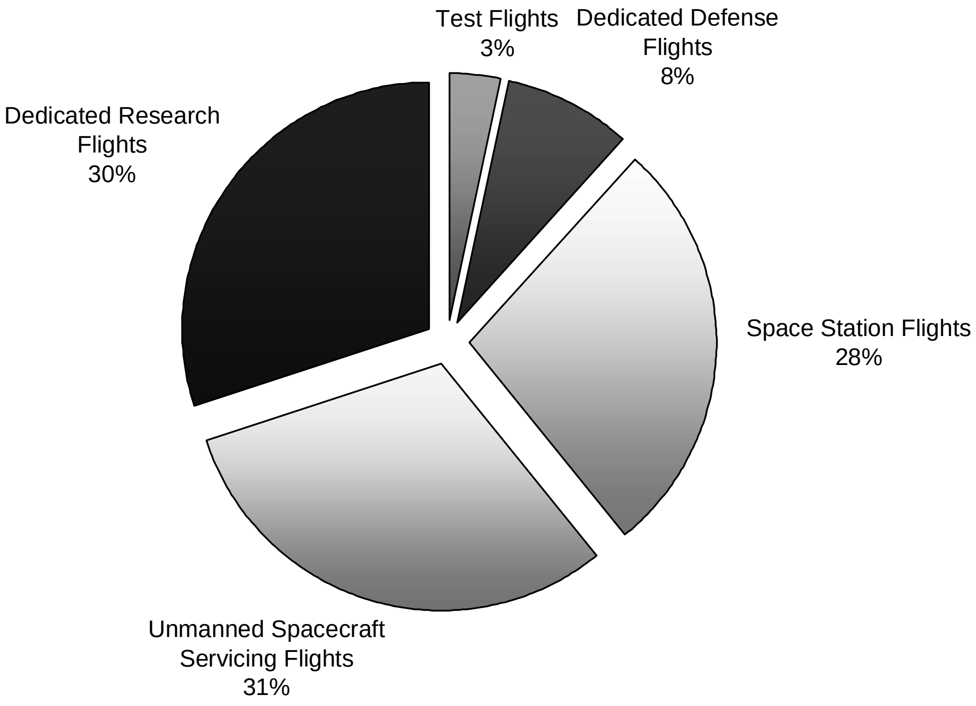

Figure 3. Total Space Shuttle Usage by Primary Mission Type.

Table 1. Achieved Shuttle Missions through Jan. 2008.[2,3]

Mission Desig.	Launch Date	Crew Size	Duration (days)	Mission Type
STS-1	Apr 1981	2	2.26	Test
STS-2	Nov 1981	2	2.26	Test
STS-3	Mar 1982	2	8.00	Test
STS-4	Jun 1982	2	7.05	Test
STS-5	Nov 1982	4	5.09	Servicing
STS-6	Apr 1983	4	5.02	Servicing
STS-7	Jun 1983	5	6.10	Servicing
STS-8	Aug 1983	5	6.05	Servicing
STS-9	Nov 1983	6	10.32	Research
STS-41B	Feb 1984	5	7.97	Servicing
STS-41C	Apr 1984	5	6.99	Servicing
STS-41D	Aug 1984	6	6.04	Servicing
STS-41G	Oct 1984	7	8.22	Servicing
STS-51A	Nov 1984	5	7.99	Servicing
STS-51C	Jan 1985	5	3.06	Defense
STS-51D	Apr 1985	7	7.00	Servicing
STS-51B	Apr 1985	7	7.01	Research
STS-51G	Jun 1985	7	7.07	Servicing
STS-51F	Jun 1985	7	7.95	Research
STS-51I	Aug 1985	5	7.10	Servicing
STS-51J	Oct 1985	5	4.07	Defense
STS-61A	Oct 1985	8	7.03	Research
STS-61B	Nov 1985	7	6.88	Servicing
STS-61C	Jan 1986	7	6.09	Servicing
STS-51L	Jan 1986	7	0.00	Servicing
STS-26	Sep 1988	5	4.04	Servicing
STS-27	Dec 1988	5	4.38	Defense
STS-29	Mar 1989	5	4.99	Servicing
STS-30	May 1989	5	4.04	Servicing
STS-28	Aug 1989	5	5.04	Defense
STS-34	Oct 1989	5	4.99	Servicing
STS-33	Nov 1989	5	5.00	Defense
STS-32	Jan 1990	5	10.88	Servicing
STS-36	Feb 1990	5	4.43	Defense
STS-31	Apr 1990	5	5.05	Servicing
STS-41	Oct 1990	5	4.09	Servicing
STS-38	Nov 1990	5	4.91	Defense
STS-35	Dec 1990	7	8.96	Research
STS-37	Apr 1991	5	5.98	Servicing
STS-39	Apr 1991	7	8.31	Defense
STS-40	Jun 1991	7	9.09	Research
STS-43	Aug 1991	5	8.89	Servicing
STS-48	Sep 1991	5	5.35	Servicing
STS-44	Nov 1991	6	6.95	Defense
STS-42	Jan 1992	7	8.05	Research
STS-45	Mar 1992	7	8.92	Research
STS-49	May 1992	7	8.89	Servicing
STS-50	Jun 1992	7	13.81	Research
STS-46	Jul 1992	7	7.97	Servicing
STS-47	Sep 1992	7	7.94	Research
STS-52	Oct 1992	6	9.87	Servicing
STS-53	Dec 1992	5	7.31	Defense
STS-54	Jan 1993	5	5.98	Servicing
STS-56	Apr 1993	5	9.26	Research
STS-55	Apr 1993	7	9.99	Research
STS-57	Jun 1993	6	9.99	Research
STS-51	Sep 1993	5	9.84	Servicing
STS-58	Oct 1993	7	14.01	Research
STS-61	Dec 1993	7	10.83	Servicing
STS-60	Feb 1994	6	8.30	Research
STS-62	Mar 1994	5	13.97	Research
STS-59	Apr 1994	6	11.24	Research
STS-65	Jul 1994	7	14.75	Research
STS-64	Sep 1994	6	10.95	Research
STS-68	Sep 1994	6	11.24	Research
STS-66	Nov 1994	6	10.94	Research
STS-63	Feb 1995	6	8.27	Station
STS-67	Mar 1995	6	16.63	Research
STS-71	Jun 1995	7	9.81	Station
STS-70	Jul 1995	5	8.93	Servicing
STS-69	Sep 1995	5	10.85	Research
STS-73	Oct 1995	7	15.91	Research
STS-74	Nov 1995	5	8.19	Station
STS-72	Jan 1996	6	8.92	Servicing
STS-75	Feb 1996	7	15.74	Research
STS-76	Mar 1996	6	9.22	Station
STS-77	May 1996	6	10.03	Research
STS-78	Jun 1996	7	16.91	Research
STS-79	Sep 1996	7	10.14	Station
STS-80	Nov 1996	5	17.66	Research
STS-81	Jan 1997	7	10.21	Station
STS-82	Feb 1997	7	9.98	Servicing
STS-83	Apr 1997	7	3.97	Research
STS-84	May 1997	7	9.97	Station
STS-94	Jul 1997	7	15.70	Research
STS-85	Aug 1997	6	11.80	Research
STS-86	Sep 1997	7	10.81	Station
STS-87	Nov 1997	6	15.69	Research
STS-89	Jan 1998	7	8.82	Station
STS-90	Apr 1998	7	15.91	Research
STS-91	Jun 1998	7	9.83	Station
STS-95	Oct 1998	7	8.91	Research
STS-88	Dec 1998	6	11.80	Station
STS-96	May 1999	7	9.80	Station
STS-93	Jul 1999	5	4.95	Servicing
STS-103	Dec 1999	7	7.97	Servicing
STS-99	Feb 2000	6	11.24	Research
STS-101	May 2000	7	9.86	Station
STS-106	Sep 2000	7	11.80	Station
STS-92	Oct 2000	7	12.90	Station
STS-97	Nov 2000	5	10.79	Station
STS-98	Feb 2001	5	12.89	Station
STS-102	Mar 2001	7	12.83	Station
STS-100	Apr 2001	7	11.90	Station
STS-104	Jul 2001	5	12.78	Station
STS-105	Aug 2001	7	11.82	Station
STS-108	Dec 2001	7	11.83	Station
STS-109	Mar 2002	7	10.92	Servicing
STS-110	Apr 2002	7	10.82	Station
STS-111	Jun 2002	7	13.86	Station
STS-112	Oct 2002	6	10.83	Station
STS-113	Nov 2002	7	13.78	Station
STS-107	Jan 2003	7	15.93	Research
STS-114	Jul 2005	7	13.90	Station
STS-121	Jul 2006	7	12.78	Station
STS-115	Sep 2006	6	11.80	Station
STS-116	Dec 2006	7	12.86	Station
STS-117	Jun 2007	7	13.84	Station
STS-118	Aug 2007	7	12.75	Station
STS-120	Oct 2007	7	15.10	Station

B. Planned Missions

Table 2 shows basic mission data for each of the 72 Shuttle missions planned through September 1987 based on NASA Flight Assignment Manifest 13000-6 from April 1982.[4] Again, this data is shown graphically in terms of primary mission in Figures 4 and 5. As an analog to Figure 1, Figure 4 depicts each of the 72 Shuttle missions as yellow circles placed at their respective launch dates but decomposed vertically by mission type. The left plot shows the planned manifest according to Table 2, while the right plot shows the achieved flights based on Table 1. While clumping has somewhat less relevance in this figure due to the limited timescale, it is interesting to note the heavy emphasis on satellite deployment, servicing, and retrieval missions in the original manifest for the Shuttle. This emphasis was carried over into implementation, as can be seen in the right plot of Figure 4 and in Figure 2. That is, although the flight rate was lower than planned, the vast majority of Shuttle missions fell into the category of unmanned spacecraft servicing flights. Interestingly, even in the first five years of the Shuttle program, the prevalence of dedicated defense missions was far from the original plans, and only two such missions flew before January 1986 as opposed to the ten that were planned (including one originating from Vandenberg Air Force Base).

Figure 5 shows more precisely the difference between the planned and actual manifests, particularly in terms of the difference in relative numbers of Department of Defense flights compared to unmanned spacecraft servicing flights: Instead of claiming 33% of Shuttle missions through FY87, defense flights accounted for only 8%. The difference was made up principally by unmanned satellite deployment flights (60% vs. 47%). It should be noted that test flights make up a greater percentage of the actual distribution than the planned distribution solely because the actual manifest had far fewer flights (almost one-third as many).[‡] Overall, even in the first few years of the Shuttle program, the vehicle needed to respond to relative mission priorities quite different from those originally envisioned. One process occurring during these years was that Shuttle operators were learning about the system and its limitations, which is interesting in that it suggests a notion of "self-induced" requirement changes whereby system priorities change due to responses to a system's own past performance rather than solely outside influences.[§]

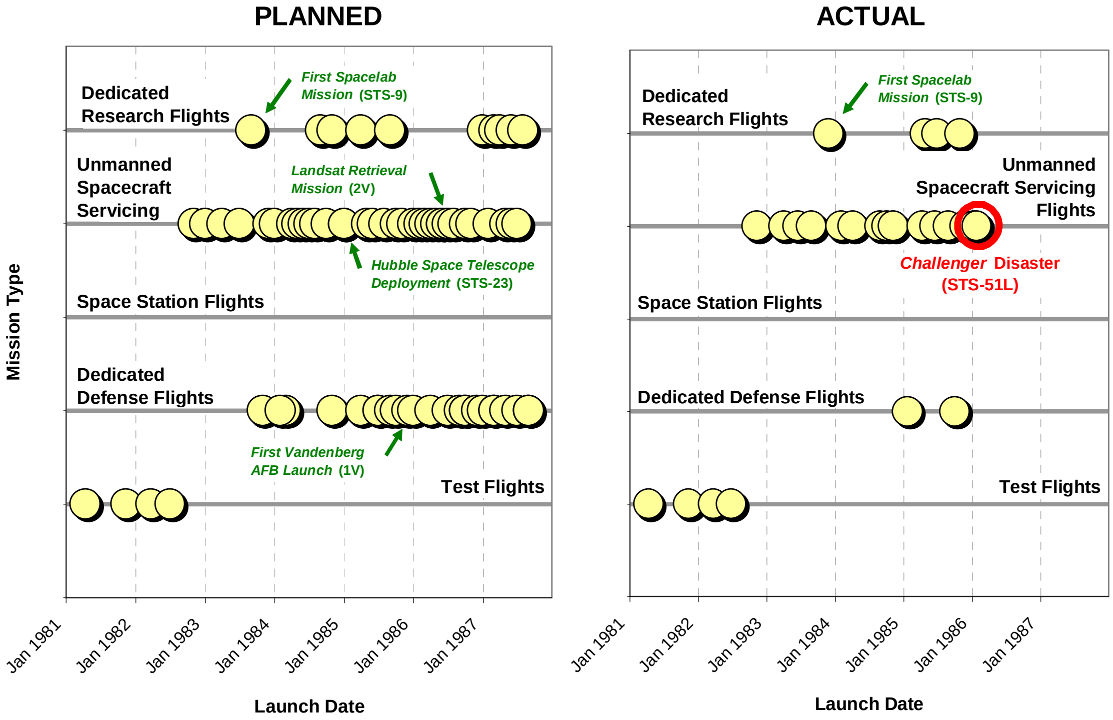

Figure 4. Event-centric representation of planned and actual Shuttle missions through Sept. 1987.

[‡] The disparity in planned and achieved Shuttle flight rates is well-documented and was a pressure identified as contributing to the *Challenger* disaster.[5] Also well-documented are the decisions that led to a low-development-cost, high-operating-cost Shuttle design.[7] In the 1982 manifest, the 72nd Shuttle mission would have occurred in September 1987. In reality, this did not occur until October 1995.

[§] This idea of a "self-induced" requirement change is of course very applicable to the changes that occurred in the Shuttle program following the *Challenger* and *Columbia* disasters.

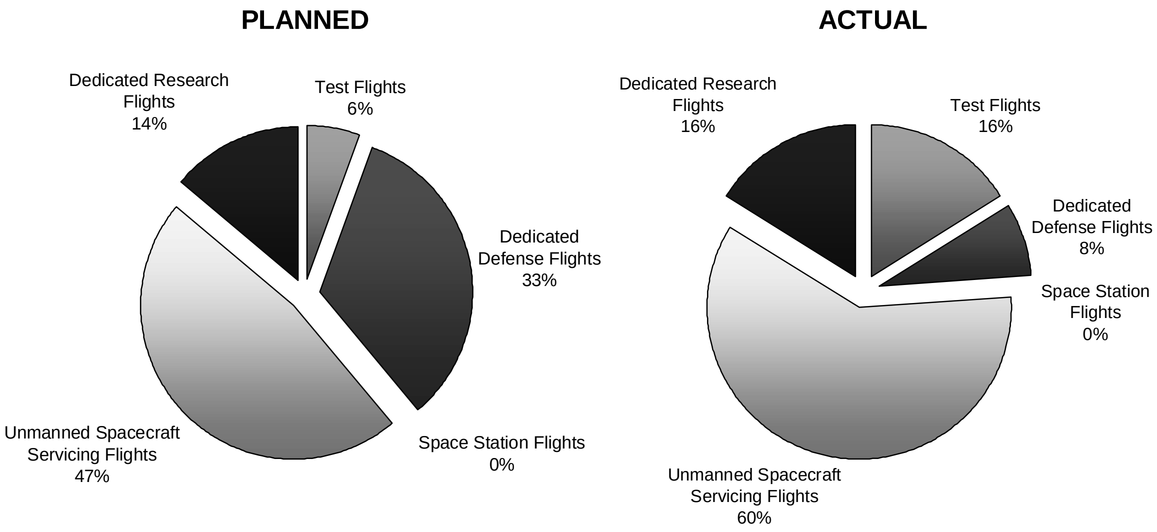

Figure 5. Planned and Actual Space Shuttle Usage by Primary Mission Type through Sept. 1987.

Table 2. Planned Shuttle Missions through Sept. 1987.[4]

Mission Desig.	Launch Date	Crew Size	Duration (days)	Mission Type
STS-1	Apr 1981	2	2.26	Test
STS-2	Nov 1981	2	2.26	Test
STS-3	Mar 1982	2	8.00	Test
STS-4	Jul 1982	2	7.00	Test
STS-5	Nov 1982	4	5.00	Servicing
STS-6	Jan 1983	4	2.00	Servicing
STS-7	Apr 1983	4	2.00	Servicing
STS-8	Jul 1983	4	3.00	Servicing
STS-9	Sep 1983	6	7.00	Research
STS-10	Nov 1983	Not Available		Defense
STS-11	Dec 1983	4	5.00	Servicing
STS-12	Jan 1984	4	3.00	Servicing
STS-13	Mar 1984	Not Available		Defense
STS-14	Apr 1984	4	7.00	Servicing
STS-15	May 1984	4	3.00	Servicing
STS-16	Jun 1984	4	7.00	Servicing
STS-17	Jul 1984	4	5.00	Servicing
STS-18	Aug 1984	4	5.00	Servicing
STS-19	Sep 1984	6	7.00	Research
STS-20	Oct 1984	4	7.00	Servicing
STS-21	Nov 1984	6	7.00	Research
STS-22	Nov 1984	Not Available		Defense
STS-23	Jan 1985	4	3.00	Servicing
STS-24	Jan 1985	4	7.00	Servicing
STS-25	Feb 1984	Not Available		Defense
STS-26	Apr 1985	6	7.00	Research
STS-27	Apr 1985	Not Available		Defense
STS-28	May 1985	4	5.00	Servicing
STS-29	Jun 1985	4	7.00	Servicing
STS-30	Jul 1985	Not Available		Defense
STS-31	Jul 1985	Not Available		Defense
STS-32	Aug 1985	2	2.00	Servicing
STS-33	Sep 1985	6	7.00	Research
STS-34	Sep 1985	Not Available		Defense
STS-35	Oct 1985	4	7.00	Servicing
1V	Oct 1985	Not Available		Defense
STS-36	Nov 1985	4	7.00	Servicing
STS-37	Dec 1985	Not Available		Defense
STS-38	Jan 1986	4	7.00	Servicing
STS-39	Jan 1986	Not Available		Defense
STS-40	Feb 1986	4	7.00	Servicing
STS-41	Mar 1986	4	7.00	Servicing
STS-42	Apr 1986	Not Available		Defense
STS-43	Apr 1986	4	7.00	Servicing
STS-44	May 1986	2	2.00	Servicing
STS-45	Jun 1986	4	7.00	Servicing
2V	Jun 1986	4	3.00	Servicing
STS-46	Jul 1986	Not Available		Defense
STS-47	Jul 1986	4	7.00	Servicing
STS-48	Aug 1986	4	5.00	Servicing
STS-49	Sep 1986	Not Available		Defense
3V	Oct 1986	Not Available		Defense
STS-50	Oct 1986	4	7.00	Servicing
STS-51	Oct 1986	Not Available		Defense
STS-52	Nov 1986	4	7.00	Servicing
STS-53	Dec 1986	Not Available		Defense
4V	Jan 1987	Not Available		Defense
STS-54	Jan 1987	6	7.00	Research
STS-55	Feb 1987	4	7.00	Servicing
STS-56	Mar 1987	6	7.00	Research
5V	Mar 1987	Not Available		Defense
STS-57	Mar 1987	Not Available		Defense
STS-58	Apr 1987	6	7.00	Research
STS-59	May 1987	4	7.00	Servicing
6V	May 1987	Not Available		Defense
STS-60	Jun 1987	6	7.00	Research
STS-61	Jun 1987	4	7.00	Servicing
7V	Jul 1987	4	7.00	Servicing
STS-62	Jul 1987	Not Available		Defense
STS-63	Aug 1987	6	7.00	Research
8V	Sep 1987	Not Available		Defense
STS-64	Sep 1987	Not Available		Defense

C. Evolution of Mission Duration Requirements

One final note regarding this data is that it allows the illustration that not only were the basic mission functionalities of the Shuttle changing with time, but so too were demands on crew time. Figure 6 shows the marked and almost continuous increase in crew-days spent per mission throughout the Shuttle program, principally due to the increase in mission duration (as opposed to increases in number of crew).[**] Interestingly, Figure 7 shows that this trend was present even very early in the program; by 1984, average crew-days on-orbit were at 42 crew-days, 60% greater than the number forecasted just two years earlier and at the limit of the Shuttle's nominal capability[8]. One plausible reason for this may have been the reality of the unexpectedly low flight rate and the desire to mitigate the effects of this by achieving more objectives per mission. Later in the program, this duration capability became desirable for research flights and particularly flights focusing on the effects of weightlessness on human physiology.[9] Recently, this capability has become desirable in the assembly of the ISS, where more Shuttle crew time on-orbit translates into more time for Shuttle crewmembers to undertake assembly tasks such as extravehicular activities and cargo transfer.

As demand for longer missions has increased, the Shuttle program has compensated with modifications to make this possible. Adaptations such as these are discussed next, and it is adaptations such as these that lend credibility to the classification of the Space Shuttle as a flexible – rather than simply a robust – space system.

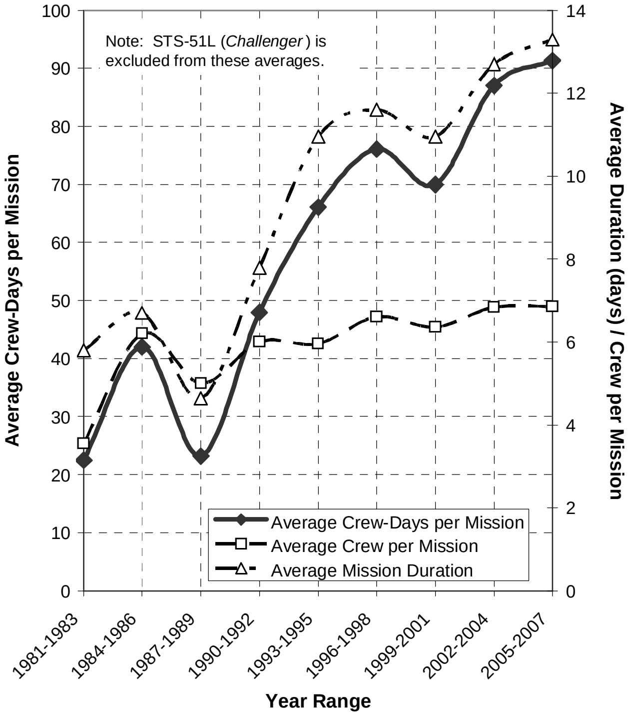

Figure 6. Average Crew-Days per Shuttle Mission through Jan. 2008.

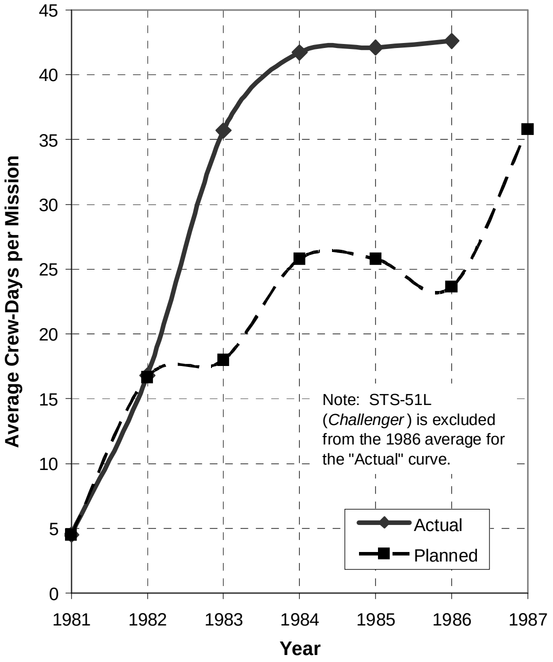

Figure 7. Average Crew-Days per Shuttle Mission through Sept. 1987.

[**] Crew-days is meant as a productivity metric and is defined as the product of the number of crew and number of days spent on-orbit for a given mission.

III. Adaptability of the Space Shuttle Vehicle

A. Flexibility through Mission-Specific Elements

As discussed earlier, a defining characteristic of a flexible system is its ability to adapt to changing environments or requirements. This implies that in a flexible system, action is taken by a user to change the system after it has been fielded. In the case of the Space Shuttle, throughout the system's nearly three-decade history, numerous adaptations have been made. With respect to the demand for multiple mission types, there have been several fairly standard Space Shuttle elements which have been addable or removable depending on the mission being flown. The mission-specific elements listed below have to a large extent acted as enablers to allow certain missions to be flown, and Table 3 concisely summarizes this information in terms of which elements were key enablers for which of the mission types for which data was shown earlier. It should also be noted, however, that although each element acted to the benefit of the Shuttle in enabling certain missions, each also imposed costs in areas of mass, power, schedule, and funding.

Table 3. Examples of Shuttle Mission-Specific Enabling Elements.

		Mission Type				
		Test Flights	Dedicated Defense Flights	Space Station Flights	Unmanned Spacecraft Servicing Flights	Dedicated Research Flights
Mission-Specific Elements	RMS			🟩	🟩	
	ODS			🟩		🟩
	Spacelab					🟩
	SPACEHAB			🟩		🟩
	EDO Pallet					🟩
	SSPTS			🟩		
	Ejection Seats	🟩				
	Additional Seats			🟩		🟩

Remote Manipulator System (RMS). Perhaps the earliest mission-specific component flown on the Shuttle, the RMS (commonly known as the Shuttle's robotic arm) was first flown in STS-2 in 1981. Through the end of 2007, 63% of Shuttle missions are known to have carried an RMS (approximately 5% of missions were classified defense missions and could also have included an RMS).[3,10] With a mass of about 400 kg,[10] the RMS primarily enabled the capture of satellites for repair or return as well as the assembly of the International Space Station.

Orbiter Docking System (ODS). In the early 1990s, all orbiters except for *Columbia* were modified such that their airlocks, which were originally located inside the crew cabin, were mounted externally in the orbiter payload bay. The resulting system was the ODS and included an external airlock, supporting truss structure, and a docking interface (see Figure 8). This enabled docking with both *Mir* and the ISS and also added significant volume to the middeck of the crew cabin which was particularly useful for stowage and crew activities during long-duration research flights. The quoted cost of the ODS was $95.2 million (FY95), and the system had a mass of approximately 1800 kg.[10]

Spacelab. First flown on STS-9 in 1983, Spacelab was the first inhabitable payload carried in the Shuttle's payload bay. With a diameter of 4.0 m and length of 7.0 m (nearly as large as the permanent European *Columbus* laboratory on the ISS), Spacelab is an example of the capability of the Shuttle to "act in some ways as a substitute for a more permanent manned station." [7] Spacelab missions were dedicated to science. The development of Spacelab was completed at a cost to the European Space Agency of nearly $1 billion (FY84), and the Spacelab mass was approximately 8100 kg (excluding external pallets).[10]

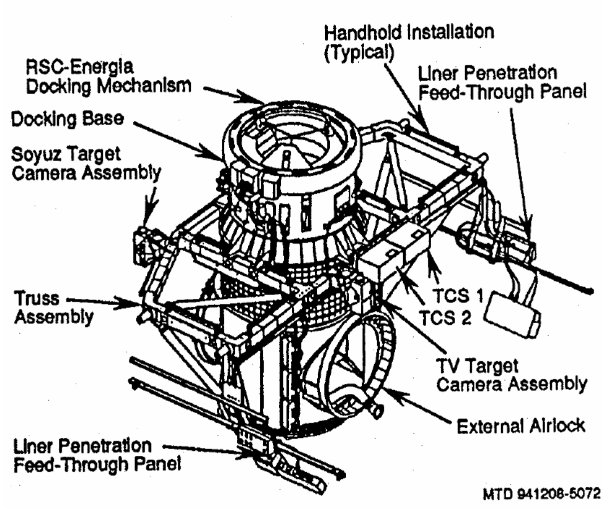

Figure 8. Orbiter Docking System from STS-71.[10]

SPACEHAB. In late 1989, the NASA Office of Commercial Programs conducted an analysis that highlighted the need for augmentation of the Shuttle middeck, which had been an effective research area but which was also severely limited in terms of the number and size of experiments it could accommodate. SPACEHAB was the response to this need. First flown on STS-57 in 1993, SPACEHAB was primarily a research facility. However, during the Shuttle-*Mir* missions, SPACEHAB became heavily used as a logistics module in which to store pressurized cargo for transfer to the Russian station. Like Spacelab, SPACEHAB was available in a single- or double-module configuration. In the single-module configuration of STS-57, SPACEHAB had a mass of 4400 kg and was 4.1 m in diameter and 2.8 m long (see Figure 9).[10]

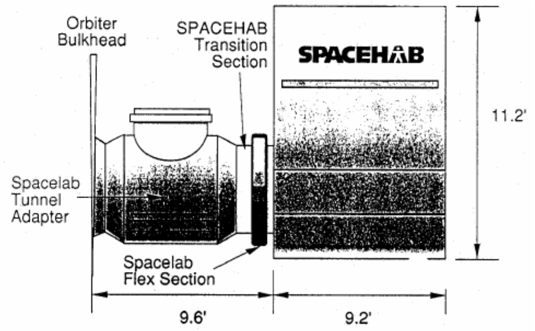

Figure 9. SPACEHAB module from STS-57. [10]

Extended Duration Orbiter (EDO) Pallet. In 1988, the Extended Duration Orbiter (EDO) program officially began as an effort to extend the maximum duration of Shuttle missions from 10 days plus 2 days of contingency (i.e. 10 + 2 days) to 16 + 2 days with the potential of expanding further to 28 days. This capability was particularly attractive to research flights and especially flights investigating the effects of spaceflight on human physiology. Upgrades were made to *Columbia* and *Endeavour* in terms of power systems, cabin atmosphere systems, available stowage space, and waste collection systems. Of particular interest is the EDO pallet mounted at the rear of the payload bay which adds four tanksets of cryogenic oxygen and hydrogen (the Shuttle nominally carries up to five tanksets) to be primarily used by the Shuttle's three fuel cells to produce electrical power. (see Figure 10) For the notional 28-day capability, an additional four tanksets would have been mounted to the opposite side of the EDO pallet.[9] The EDO pallet had a mass of approximately 1600 kg and first flew on *Columbia* on STS-50 in 1992. Because of the EDO capability, the maximum duration of a Shuttle mission was 17.7 days (STS-80), and the maximum number of crew-days on the Shuttle was 118 (STS-78). The latter metric is particularly remarkable since this is 40% higher than the first Skylab space station mission in which a crew of three spent 28 days in space.[10]

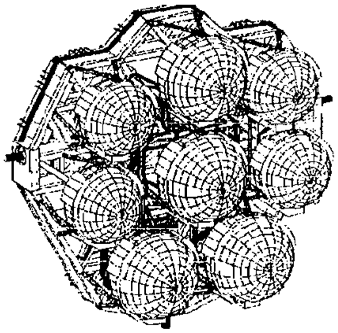

Figure 10. Rear view of the EDO Pallet which could be mounted in the rear of the Shuttle payload bay.[9]

Station-Shuttle Power Transfer System (SSPTS). In 2007, a new capability was fielded for the Space Shuttle to receive power from the ISS while docked. The SSPTS, installed on *Discovery* and *Endeavour*, was an adaptation of a previous power transfer device called the Assembly Power Conversion Unit (APCU) which had been used to allow power transfer from the Shuttle to the ISS during early assembly missions. As a result, the Shuttle can remain on-orbit for 3-4 additional days to allow for additional crew assembly and cargo transfer activities.[10]

Ejection Seats. As a risk reduction measure, ejection seats were included on *Columbia* for the first four two-crew Shuttle missions. The crew wore modified Air Force high-altitude pressure suits and had the ability to eject from the spacecraft in the event of a catastrophic failure during launch.[10] Although crew escape systems were studied for larger crews, none were pursued because of their large impacts on the vehicle.[11] The ejection seats from the Shuttle test flights may be seen as enabling those missions with relatively low impact to the vehicle.

Additional Seats. The original crew cabin arrangement of the Shuttle was configured for a crew of four for a seven-day mission. These four crew would be seated on the flight deck of the Shuttle, and the two rear mission specialist seats were to be removed on-orbit.[8] As shown in Figure 6, the average crew per flight has gradually increased to seven, and this has been accommodated by the addition of three seats on the middeck. It is particularly interesting to note the few occasions when an additional seat was added to accommodate eight crew, such as on the 1985 Spacelab mission STS-61A and the 1995 STS-71 mission to *Mir* which returned a five-member Shuttle crew plus a three-member *Mir* crew. Additionally, contingency plans exist which allow stowage and sleeping provisions to be replaced with additional seats to allow up to ten astronauts to be returned to Earth on a rescue mission.[12]

It should be noted that, although no elements in Table 3 are shown to correlate with the category of dedicated defense missions, this is not an indication that no correlation existed. Rather, since information is not available on the purpose of these missions, it is not possible to definitively associate elements as enablers. For example, if any dedicated defense missions retrieved or repaired satellites, the RMS would certainly correlate.

An observation of note from Table 3 is that many of the elements listed above were fielded for the purpose of adapting to the initial low-priority (or nonexistent) missions of dedicated research flights and space station flights. That is, most of the elements above were enablers for the missions that evolved as discussed earlier (e.g. see Figure 2). Had engineering solutions such as these not been designed and fielded, the Shuttle would not have been able to adapt to its changing requirements, which often included increased power, crew size, and duration. Because the Shuttle was able to adapt, these requirements could be met without requiring the design of a completely new system.

B. Additional Instances of Flexibility

In some instances, the Shuttle has exhibited flexibility with respect to parameters other than mission type. For example, the recommendations resulting from the investigation of the 2003 *Columbia* disaster imposed requirements for inspecting Shuttle thermal protection systems while on-orbit. A key instrument in achieving this was the Orbiter Boom Sensor System (OBSS). This 15.2 m extension to the Shuttle RMS enabled the crew of the Shuttle to conduct laser and visual scans of Shuttle surfaces normally out of visual range.[10] The OBSS is carried in the Shuttle payload bay opposite the RMS and serves as an enabler for all flights after *Columbia* given the new requirements arising from the Columbia Accident Investigation Board.

When discussing the adaptability of the Shuttle, it is also difficult to ignore concepts which have been proposed to upgrade major components of the system. Figure 11 shows a candidate strategy for Shuttle evolution from 1989 which proposes adaptations to the Shuttle. Note that the Block II concept uses essentially the same External Tank and Solid Rocket Boosters (SRBs) but upgrades the Shuttle orbiter itself. The Block III concept includes liquid fly-back boosters which result in performance and operational benefits when they replace the traditional SRBs. Additionally, Figure 11 shows adaptations that would allow the Shuttle to be flown in an unmanned mode for certain missions. While none of these large modifications came to fruition, they are still legitimate examples of at least the theoretical flexibility of the Shuttle. However, as Ref. 11 notes, "Where the evolutionary process ceases and development of a totally new system begins is one of the issues that must be addressed in developing an evolution strategy." In the case of the Space Shuttle, Shuttle-derived vehicles have been quite popular as design concepts and to some extent have defined NASA's new Ares I and Ares V rockets. In this latter sense, it might be argued that the Shuttle system was flexible enough to be modified (albeit to the point of redesign) to fly to the Moon.[††]

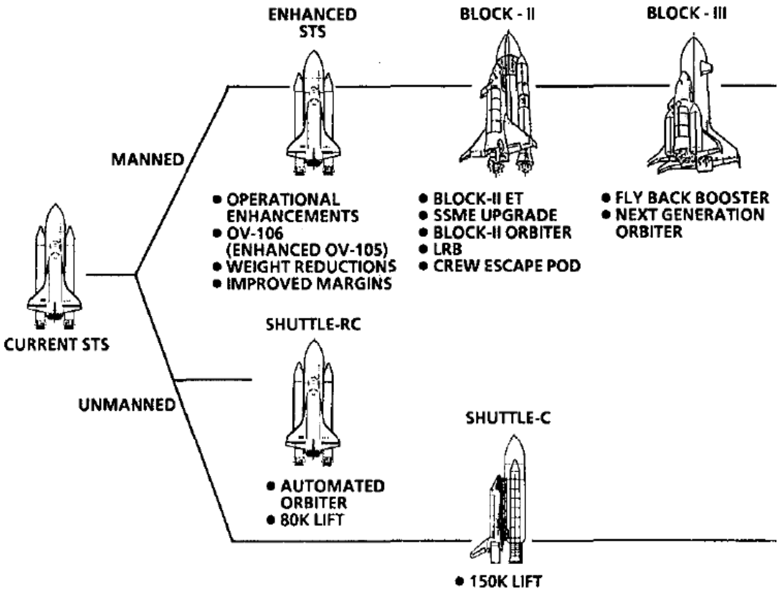

Figure 11. Candidate Shuttle Evolution Strategy from 1989. [11]

[††] As mentioned earlier, the ideal flexible system is one in which a minimal change to the system itself enables a large change in functionality or performance. By this definition, a large change in functionality accompanied by a large change in the system itself would likely be only moderately flexible (e.g. using Shuttle-derived components to return to the Moon).

IV. Conclusions

In summary, this paper has presented data on the evolution of mission requirements over time for 120 missions performed by the U.S. Space Shuttle over a period of approximately 27 years. Distinct trends in this data in the time domain – as well causes of these trends – have been identified, and 1982 manifest data serves as a confirmation that these trends were not originally anticipated in the timeframe in which they occurred. Finally, examples have been presented of engineering modifications that allowed the Shuttle to adapt and accommodate these requirement changes.

An important conclusion from this paper is that, in adding, removing, or modifying elements of its design to adapt to changing mission requirements, the Shuttle has demonstrated substantial flexibility. It is important to distinguish this from the concept of robustness.[‡‡] It is also important to note that this paper has predominantly focused on flexibility with respect to mission type (i.e. has asked the question, "What adaptations has the Space Shuttle made with respect to changes in the type of mission it is required to perform?"). Just as in the case of robustness, it is meaningless to ask for the flexibility of a system without specifying (either implicitly or, preferably, explicitly) the uncertainties or dispersions to which the system is subject. For example, one could say that the Shuttle is quite robust and quite flexible with respect to long-term changes in mission type but not with respect to launch day weather conditions.

A. Modification versus Redesign

One idea that arose in the discussion of large-scale Shuttle evolution strategies (i.e. strategies to include unmanned variants, fly-back boosters, and other major upgrades) was the difference between implementing flexibility-enabled options and total redesign. That is, in the extreme case for a flexible system, modifications may become so extensive that the system no longer resembles its original form and is essentially a new vehicle. Of course, if these modifications can be made to achieve a given requirement at a cost (monetary or otherwise) lower than designing a new system from scratch, then flexibility has performed as intended. If the cost to modify is greater than the cost to redesign (and attain the same performance), then redesign is the logical choice. Methods to systematically evaluate such modification costs and the resulting benefits *during selection of an initial design* are key developments that need to be made in order to rigorously evaluate flexible system alternatives.

Still, the question arises of "Where is the line drawn between calling a new design a redesign and calling it a highly modified design?" Although this is partially a question of semantics, a useful operational definition may be that a particular design is a modification if one can define the interfaces on the existing system to which new components are added or from which old components are subtracted. In the case of the Shuttle, all eight modifications presented in this paper interfaced to the existing Shuttle through at least electrical connections or structural members. However, it is difficult to argue this is true for the example of the Block II Orbiter from Figure 11. While this is by no means a final definition, it may be helpful as a starting point.

B. Remaining Questions

An important element in the study of the history of flexible space systems is knowledge of the design processes that created these systems. For the Space Shuttle, the question arises of whether the original designers intended the design to be as flexible as it was, and if not, how flexible was the Shuttle intended to be (and how was this measured)? It is fairly clear, for example, that the Shuttle was meant to be robust in that it could carry a wide variety of payloads (for example, a wide variety of satellites could be carried to orbit). Additionally, the diameter of the Shuttle payload bay was designed specifically to accommodate modules for an eventual space station.[7] In terms of flexibility, a paper dated as early as 1978 (three years before the Shuttle's maiden flight) exists on "Space Shuttle Orbiter Habitability *and its Extensibility* [emphasis added]".[8] Overall, a study to examine the integration of flexibility considerations in design processes (such as for the Space Shuttle) would be of high interest.

Another interesting step would be the decision processes involved in the creation of programs dedicated to adapting the Shuttle to new missions. That is, what trades were completed (for example, in terms of mass, cost, and schedule impacts or projections) to result in the decision to extend the Shuttle duration to 16 days in particular with potential expansion to 28 days in the Extended Duration Orbiter program?

[‡‡] For the Space Shuttle, robustness would deal with design characteristics that remained static but which also allowed the vehicle to accommodate a broad range of missions. These are also important and include characteristics such as payload bay size, payload mass capacity, and wing size (which allowed for cross-range and would have enabled single-orbit polar missions[7]).

Overall, the data presented in this paper on the Shuttle's changing mission requirements and its methods of adaptation have developed a substantial case for the importance of flexibility in the design of space systems. Further, the questions that have arisen as a result of this study highlight the need for the development of consistent metrics for characterizing and quantifying a system's flexibility, and trading that flexibility against other performance metrics or resources. It is hoped that the data and discussion in this paper have proven insightful to engineers and informative to decision-makers dealing with the design of future (flexible) space systems.

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