31. Chapter
Wear and Tear – Mechanical –

Ted Swanson

Introduction

The focus of this chapter is on the long term wear and tear, or aging, of the mechanical subsystem of a spacecraft. The mechanical subsystem is herein considered to be the primary support structure (as in a skeleton or exoskeleton) upon which all other spacecraft systems rest, and the associated mechanisms. Mechanisms are devices which have some component that moves at least once, in response to some type of passive or active control system. For the structure, aging may proceed as a gradual degradation of mechanical properties and/or function, possibly leading to complete structural failure over an extended period of time. However, over the 50 years of the Space Age such failures appear to be unusual. In contrast, failures for mechanisms are much more frequent and may have a very serious effect on mission performance.[1]

Just as on Earth, all moving devices are subject to normal (and possibly accelerated) degradation from mechanical wear due to loss or breakdown of lubricant, misalignment, temperature cycling effects, improper design/selection of materials, fatigue, and a variety of other effects. In space, such environmental factors as severe temperature swings (possibly 100's of ^{0}C while going in and out of direct solar exposure), hard vacuum, micrometeoroids, wear from operation in a dusty or contaminated environment, and materials degradation from radiation can be much worse. In addition, there are some ground handling issues such as humidity, long term storage, and ground transport which may be of concern.

This chapter addresses the elements of the mechanical subsystem subject to wear, and identifies possible causes. The potential impact of such degradation is addressed, albeit with the recognition that the impact of such wear often depends on when it occurs and on what specific components. Most structural elements of the mechanical system typically are conservatively designed (often to a safety factor of greater than ~1.25 on yield for unmanned spacecraft) but do not have backup structure due to the added mass this would impose, and also due to the fact that structural elements can be accurately modeled mathematically and in test.[2] Critical mechanisms or devices may have backups, or alternate work-arounds, since characterization of these systems in a 1g environment is less accurate than structure, and repair in-space is often impossible.

Causes of Mechanical Aging

Mechanical aging is not necessarily the same phenomena as events that are typically classified as "failures". Both aging and failures will be addressed in the following discussion as failures may be viewed as an "infant mortality" type of aging.

Some events which are traditionally classified as "failures" are due to poor design, poor quality, or improper selection of materials. One proximate cause of such mechanical failure is the stresses

induced by acceleration forces such as those experienced during launch, orbital maneuvers, deployment of antennas and other such structures, and planetary entry/landing. Other failures are caused by poor ground handling (e.g., contamination, excessive testing for vibration or temperature extremes, etc.) or workmanship issues. Many mechanical or mechanism failures are caused by exposure to, and continuous operation within the space environment. Many of these failures may be more commonly termed as "aging" effects. Space environmental effects include; the thermal environment, plasma, micrometeoroids and space debris, solar thermal effects, magnetic fields, and changes in the gravitational environment.[3] Some of the fundamental causes for failure by space environmental effects are discussed in later in this chapter and elsewhere in this book, and will thus be addressed in this chapter only as they apply to mechanical subsystems.

It should be recognized that there are several classifications of what constitutes a "failure". Different groups define and classify "failures" in different ways. For the purposes of the following discussion, only "significant " failures, which are generally defined as being an event which results in a loss of 33% or more of a mission's objective or instrument's objective, will be considered.[4]

Failure/Aging due to Poor Design, Poor Quality, or Improper Materials

Spacecraft mechanical systems, and especially mechanisms, are often a one-of-a-kind design. [5] This is especially true for spacecraft/instruments intended for missions of exploration or for science missions. Some components that are common to many spacecraft, such as a solar drive mechanisms, gyroscopic reaction wheel assemblies, motors, mechanical louvers, etc., may share a common design and be manufactured in lots. But there are often variations in how they are used and the environment to which they are exposed that create unique design challenges. Even communication satellites are typically made in lots of no more than a few dozen. Hence, mechanical subsystems may lack the design heritage and wider use that other subsystems might enjoy.[6,7] This lack of a broader data base means less experience with a given design, and this may contribute to design flaws. In addition, development of a reliability model to accurately predict the probability of failure is nearly impossible due to the low sample size that can be used in the analysis.

The effects of poor design, poor quality, or improper material choice may manifest themselves very quickly, such as at launch, or result in a degradation (possibly leading to failure) over time. A not uncommon example of long term degradation would be failure of a gyroscopic stabilizer wheel due to problems with the bearings. Moving parts, such as bearings, motors, and gears often have lubrication that may eventually outgas to space, become dislocated from the moving parts (due to migration, lubricant is driven away from the hot spots). Moving pars may also become stuck due to friction from wear or thermally induced expansion/contraction of the materials. These have been identified as common causes of failure and for this reason moving parts are often avoided, if possible. Deployment mechanisms have sometimes failed to engage fully or at all, leading to problems with the power, thermal, or communications subsystem. A classic example would be the failure of the solar array/micrometeoroid shield to properly deploy on Skylab in 1973, which caused power problems and excessive temperatures until makeshift repairs could be performed. A more recent example would be the failure of the solar array on the Mars Global Surveyor to latch properly (due to a damper arm failure) which resulted in a flight plan change.[8]

Data collected over the last few decades shows that design flaws are becoming fewer, at least for missions and applications for which we are gaining experience.[9] Ground testing and a sound quality control program have generally mitigated mechanical design and quality issues. However, as humans move further out into the Solar System and beyond, we will be exposing

our spacecraft to ever more challenging environments, some of which are not as well understood as the near Earth environment. The near Earth environment, as harsh as it may seem when compared to terrestrial applications, is actually relatively benign compared to the Moon, outer planets, or nearer to the Sun. This will complicate the design of all subsystems, including mechanical, and often demand more sophisticated and complex designs that have fewer margins for error.

Ground testing and verification is another issue that may be complicated due to the difficulty in precisely replicating long term space exposure via traditional ground testing techniques. Space environmental simulation testing, such as thermal cycling in a vacuum, launch vibration loads, acoustic loads, radiation effects, etc., is normally performed in a piecemeal fashion due to practical and cost limitations. This approach has proven to be very effective when done properly, but it does not really address long life issues that may only manifest themselves after decades, centuries, or millenniums of time.

It should be noted that it important to test the spacecraft to the limits of what it will be exposed to in space, with some margin, and to avoid either under or over testing. This is often referred to as the "test as you fly, fly as you test with some margin" philosophy.[10,11] Testing to a less stringent environment can clearly lead to premature failure due to the actual use exceeding the mechanical and/or thermal environment the spacecraft was designed for, and qualification tested to. However, over-testing by either going to excessive levels or excessive cycles, beyond a reasonable margin above the expected environmental limits, can lead to stressing the mechanical subsystem beyond its design limits. This can lead to performance deterioration or outright failure. Accordingly, it is vital to be able to accurately predict the mechanical stress that the spacecraft will be exposed to in its intended service. A great deal of sophisticated analysis is typically employed to ensure accuracy, and ground testing is intended to "qualify" a given piece of hardware to the calculated exposure limits.

Improper material selection is really a design issue which should be mitigated through experience with similar applications, knowledge of material performance in the anticipated environment, and a thorough ground test program. However, examples of failure through improper material selection continue to occur, albeit at a reduced rate due to the maturing of the industry.

Failure/Aging due to Acceleration Forces

Acceleration forces can have a significant impact on both the spacecraft's structure and mechanisms, and careful design is needed to mitigate these effects.[12] The result of improper design or poor quality may be manifested as a catastrophic failure or through a delayed failure caused by material fatigue. Fatigue is a particularly difficult issue, as if is more difficult to predict and can be significantly impacted by micro-cracks and other small flaws.

Mechanical loads may be either static or dynamic. Static loads may be imposed externally, such as by gravity during spacecraft assembly/integration/testing, or they may be self-contained such as from stored propellants which are under pressure (typically temperature dependent), preloads from tightening a bolt, or thermoelastic stresses from temperature changes which cause materials to expand/contract. Dynamic loads include launch thrust vibration, air pressure waves during launch while in the atmosphere, shock impulse loads from the pyrotechnic devices used to perform stage separation, stresses from orbital maneuvering, and reentry/landing loads. It should be noted that theses dynamic loads are expressed over a fairly wide frequency range, and may vary in intensity during the acceleration/deceleration event.[13] These transient dynamic loads may initiate a fatigue failure, which might be completed by cyclical stresses occurring during normal operations while in space. Cyclical stresses while in orbit or in transit may be due to thermally induced cycling (e.g., the spacecraft going in and out of exposure to the sun), operation

of equipment that has some vibration, or some other cause. The combined effect of thermally induced stresses with additional mechanical stress can be particularly damaging for structures made of composite materials as this may cause microcracking.[14] For many modern rockets, peak axial acceleration is on the order of 3 to 5 g's, meaning that the mechanical stress applied to the structure is 3 to 5 times that normally applied by gravity. However, depending on how and where a component is mounted it may experience significantly higher transient acceleration forces, on the order of 10's of g's. For example, many components are, in effect, mounted in a cantilever fashion, which can significantly increase their g loading.

In addition to the basic structure, which clearly must survive launch without functional damage, there are typically mechanisms, such as gyroscopic stabilizer wheels, deployment devices, turntables for scanning instruments, filter wheels, motors, shutters, etc., which need to operate once launched, either as a single event or routinely. Depending on their design, some mechanisms may require "launch locks" to constrain moving parts or bypass the load path during the violent launch event. Failure of the launch locks to properly engage, or to release when so commanded, or to release too early, are additional causes of an infant mortality type of aging. Additionally, mechanical components which contain pressurized fluids, such as propulsion lines/tanks and heat pipes, are at risk for developing leaks (due to weld or seal failure, collisions with micrometeoroids or space junk, etc.) which can also lead to early failure.

Failure/Aging due to Poor Ground Handling or Workmanship

There have been a variety of premature failures caused by poor handling during integration and testing, or while the spacecraft is transit between assembly, testing and/or launch facilities. Other failures have been caused by simple poor quality workmanship. Stringent quality control procedures are typically employed to prevent such unnecessary problems, but they continue to occur. Part of the issue is the complexity and interrelationship between the spacecrafts various subsystems, which can result in unintentional and unrecognized damage to a component not obviously associated with one that is being worked on. Sometimes cost and/or schedule will drive the management to take risks which later prove to be poor decisions.

Typical problems in ground handling tend to focus around excessive vibrations during transit, exposure to excessive temperatures or humidity during transit, and contamination from particulate or molecular sources. From a mechanical subsystem perspective, excessive vibrations while still on the ground risk the loss of lubricant in gears or sliding components, or misalignment of critical components such as optics and lasers. For example, the high gain antenna on Galileo got stuck and could not be released while in transit to Jupiter. It is conjectured that this might have been caused by misalignment/loss of lubricant during its numerous transits on highways to and from the launch facility.

The presence of excessive contamination on a spacecraft, particularly molecular buildup on sensitive optics and precise mechanisms, is another risk to long term life. This is typically caused either by assembly and/or testing in a dirty (i.e., non-controlled) environment or molecular out-gassing of volatiles from within the materials used to assemble the spacecraft. This will occur under the hard vacuum of space (or a thermal vacuum space simulation test) and is accelerated by higher temperatures. Proper material selection and an appropriate approach to contamination control during assembly/testing/shipping are needed to avoid this potentially serious problem.[15]

Failure/Aging due to the Natural Space Environment

The natural space environment can have a very significant impact on a variety of spacecraft subsystems, including mechanical. By natural space environment, it is meant the environment that is present in space independent of the presence of the particular spacecraft in question. It includes both naturally occurring phenomena, such as radiation and solar illumination, as well as man made objects such as space debris. More specifically it includes the following nine

environments: the neutral thermosphere, thermal environment, plasmas, meteoroids and man-made space debris, the solar environment, ionizing radiation, geomagnetic field, gravitational field, and the mesosphere. These environments may cause either sudden or, more likely, gradual deterioration of a spacecraft subsystem leading to eventual failure. Since such degradation is the result of the "natural space environment", such a failure may be better termed true "aging".

The space environments which have the most impact on the mechanical subsystem include; the thermal environment, plasma, micrometeoroid/space debris, and solar environment. Magnetic fields, gravitational effects, and the mesosphere may have secondary effects. The thermal environment is coupled to the solar environment, and is driven by the presence or lack of solar illumination, and by any planetary infrared radiation or reflected solar radiation that the spacecraft may be exposed to. The thermal properties of the exposed surfaces of the spacecraft will determine how hot or cold each surface gets in response to this incident radiation. This has a significant impact on the placement of various spacecraft components, such as radiators, so that they may be maintained within acceptable temperature limits. Additionally, if the spacecraft is exposed to a variable thermal environment, such as will occur for spacecraft in Low Earth Orbit, on the lunar surface, or on a planetary surface, then it will be alternately heated and cooled. For example, a spacecraft on the surface of the moon may be exposed to an effective thermal environment of over 100 ^{0}C during the lunar day, which falls to perhaps – 200 ^{0}C during the lunar night. This temperature differential of 300 ^{0}C or more can cause serious problems due to the natural expansion and contraction of materials in response to temperature changes. This may lead to fatigue cracks which can ultimately fail, especially when under an additional load [16]. Composite materials may be particularly susceptible to this phenomenon.[17]

Plasma naturally occurs in the upper atmosphere (above 90 km) as a result of solar radiation [18]. It can cause mass loss from erosion, arching and sputtering, and thus change structural dimensions. A common phenomenon is the splitting of the O_2 molecule into atomic oxygen, which is highly reactive with certain polymers used in spacecraft construction. An example is the aluminized Kapton commonly used for insulation/thermal control. The resulting deterioration of such materials due to atomic oxygen exposure can have significant impacts on the thermal control subsystem leading to problems with the mechanical subsystem, especially mechanisms. Another common effect of solar radiation in the upper atmosphere is the stripping of electrons off of an atom's outer shell. This creates plasma of positively charged atoms and negatively charged electrons, which can cause a charge differential across a spacecraft. Discharges move material from one location to another creating dimensional changes, as well as having significant impacts on the spacecraft's electrical subsystem..

Micrometeoroid/space debris is an increasing problem due to the long life of some "space junk". Space junk is material left over from launches or generated by the intentional or unintentional breakup of spacecraft. While these particles may be small, they are traveling at a very high velocity differential relative to a given spacecraft. For example, a small, 90 gram particle will impart over 1 MJ of energy from an impact.[19] There are numerous examples of such micrometeoroid/space debris hits [20]. Just through September of 1993 the Shuttle Program had to replace over 46 Orbiter windshields due to impact damage. After the December 1993 Hubble Servicing Mission the retrieved solar array showed over 5000 micrometeoroid impacts over its 4-year life in space. And late in 1989 when the Shuttle was retrieving the LDEF spacecraft, a picture was taken showing a large piece of debris, with a relative velocity of about 170KM/hr, passing between LDEF and the Shuttle when they were only 660 feet apart. A collision might have been catastrophic.[21]

Failure/Aging due to Planetary Environments

Entry into, landing, and long term survival on a planetary body may incur severe stresses on the mechanical subsystem. This is particularly true if the planet, or moon, has an atmosphere. Depending on how it is accomplished, reentry into a planetary atmosphere may be at hypersonic speeds and incur high "g" forces from deceleration. The energy associated with the change in speed will be dissipated as heat. Both the resulting mechanical stress and the weakening of material properties from the elevated temperatures will place significant demands on the mechanical structure. To help mitigate these effects a variety of techniques are used, such as an ablative heat shield which may be jettisoned during landing, parachutes, and some sort of landing technology such as reverse thruster rockets, inflatable balloons, and/or collapsible structure to absorb the landing shock.

Once on the surface, the spacecraft will be fully exposed to the ambient environment, which may be extremely harsh. These conditions vary tremendously depending on the planet or moon involved, and the spacecraft will have to be designed to survive (for whatever time is intended) in this environment. For example, the atmospheric pressure on the surface of Venus is 90 times that of Earth and the temperature is approximately 430 ^{0}C. The atmosphere is nearly pure carbon dioxide, but higher in the atmosphere there are significant quantities of sulfuric acid. The moons of the outer planets, which are of significant interest as they may have subsurface water oceans or pre-biotic compounds, are extremely cold (about –200 ^{0}C). For example, Titan, Saturn's largest moon, has a thick atmosphere at -180 ^{0}C composed primarily of nitrogen, with clouds of methane and ethane. It has atmospheric circulation with rain and lakes of liquid methane. Some moons, such as those of Jupiter, are exposed to an intense radiation environment. The longevity of mechanical systems in such environments is clearly a function of the design and material choices, and will no doubt be affected by unknown corrosive and/or other environmental forces particular to a given planet or moon.

HST to JWST Mechanical Evolution

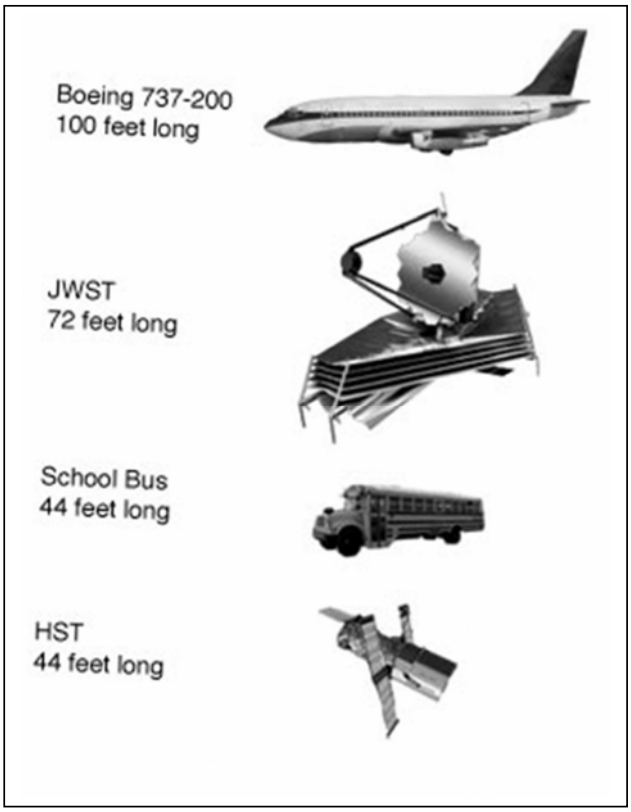
The comparison of the Hubble Space Telescope to its scientific replacement the James Webb Space Telescope is representative of the ever involving mechanical structures in space. The model of the JWST with progam team as shown in figure 31-1 demonstrates the growth of mechanical complexity and team size to support these large spacecraft developments.

Deleted: at the mall at Goddard Space Flight Center

Figure 31-1 Model of JWST (NASA)

Deleted: at GSFC

Mechanical engineering in space has evolved in complexity, size and allows greater support for increase mission functionality. Logarithmic increases in launch lift, combined with years of experience in materials in space applications enable greater functionality to accomplish significantly more tasking science drivers.



Launch:

The Hubble Space Telescope orbits around the Earth at an altitude of ~570 km above it.

JWST will not actually orbit the Earth - instead it will sit at the L2 Lagrange point, 1.5 million km away! Because HST is in earth orbit, it was able to be launched into space by the space shuttle. JWST will be launched on an Ariane 5 rocket. Larger lift capability enables larger structures as shown in figure 31-2.

Size:

HST is 13.2 meters (43.5 ft.) long and its maximum diameter is 4.2 meters (14 ft.) whereas, JWST's

sunshield is about 22 meters by 12 meters (72 ft x 39 ft). That is about the size of a tennis court. HST's mirror is a much smaller 2.4 meters in diameter and its corresponding collecting area is 4.5 m^2. Figure 31-3 demonstrates the larger primary mirror area.

Mission Science and Wavelength:

JWST will have a 6.6 meter diameter primary mirror, which will give it a significant larger collecting area than the mirrors available on the current generation of space telescopes; about 7 times more collecting area than HST. JWST will also have significantly larger field of view than the NICMOS camera on HST (covering more than ~15 times the area). Significantly, JWST will observe primarily in the infrared in order to study the origin and evolution of galaxies, stars and planetary systems by providing infrared imagery and spectroscopy. JWST's four instruments will provide wavelength coverage from 0.6 to 28 micrometers (or "microns. The instruments on HST can observe a small portion of the infrared spectrum from 0.8 to 2.5 microns, but its primary capabilities are in the ultra-violet and visible parts of the spectrum from 0.1 to 0.8 microns.[22]

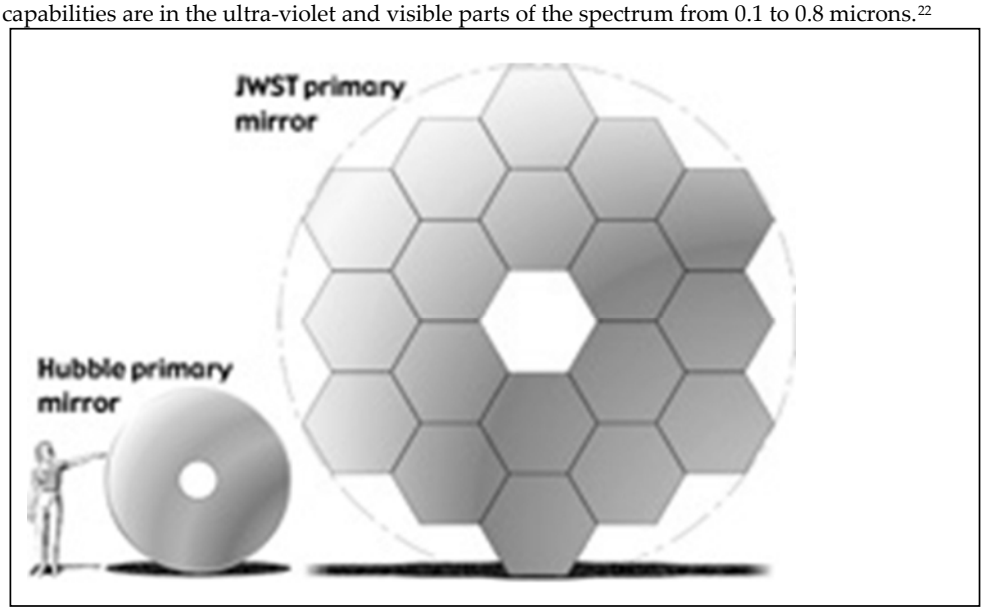


Figure 31-3. Comparative sizes HST versus JWST primary mirror (NASA)

Comment; this figure need better graphics or delete it….too fuzzy. I could not find anything better.

Trends in Spacecraft Design affecting Aging

Over the 50 years of the Space Age, we have learned a great deal on how to design and operate spacecraft to enhance their odds for mission success and long life. The major driver for mechanical aging, the space environment, hasn't changed but our knowledge of this demanding environment has improved greatly and hence we have changed the materials and techniques used to build spacecraft. Our technologies have also advanced in many areas. This improved understanding of the environment and advanced materials/technology have lead to reduced mechanical failures for the typical spacecraft in low Earth orbit.

Deleted: would

Deleted: giving JWST around

Deleted: and will have four science instruments that can take images and spectra of objects.

Formatted: Font: Not Bold

Deleted: se

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Deleted: The

Deleted: "). JWST's instruments will work primarily in the infrared range of the electromagnetic spectrum, with some capability in the visible range.

As composites offer the opportunity for reduced structural mass and the ability to tailor thermal, electrical, and radiation transparency properties, the trend is for their increased use on future spacecraft. While generally robust in the space environment, they can fail in manners that solid metals do not. Composite properties may vary greatly depending on material selection and fabrication, and they are often non-isotropic in mechanical, thermal, and electrical properties. For example, they are more subject to micro-cracks which may lead to delamination or fatigue failure. Failures or design/fabrication flaws may also be more difficult to detect using traditional inspection techniques, and also more difficult to repair. Another emerging trend, again to save mass and also packing volume, is towards inflatable structures to be used as habitats, reflectors, storage containers, shields, balloons, or as structural members such as beams. Such subsystems may fail due to improper inflation, improper or incomplete hardening (if employed), radiation damage, leaks of the pressurant (if employed), as well as to the harsh environment of space.

Conclusion

Formatted: Font: Bold

As we send spacecraft to ever more demanding environments, such as very near the sun, to our moon, or to the moons of the outer planets, the stresses induced by the environment will increase. To accommodate this increasingly severe environment and typically more challenging mission objectives, these spacecraft will become more sophisticated and advanced in their design and materials choices. Additionally they will often need to last decades, instead of years. This might even lead to material deterioration (and hence mechanical deterioration) from the expansion/contraction caused by thermal cycling and extreme temperatures. The possibility of long term radiation damage, especially for some composites, may also increase with long exposure. Hence, a future where spacecraft go to ever more environmentally demanding locations, with more sophisticated equipment, and operating for a much longer timeframe will increase the risk of failure from environmental factors, material selection, new technologies, and/or a combination of such considerations. Clearly our designs and materials must improve, and with such improvement will come improved performance and durability. But failures, whether from inadequate design, poor material choices, misunderstanding of the environment, inadequate testing, poor workmanship, or human error will continue to occur as space is a harsh and very unforgiving environment. Our goal is to anticipate and meet the challenges with an ever increasing capability.

Figures

Figure 31-1 Model of JWST (NASA)

Deleted: at GSFC

Figure 31-2. Comparative sizes HST and JWST (NASA)

Figure 31-3. Comparative sizes HST versus JWST primary mirror (NASA)

REFERENCES

[1] Newell, J and Oberhettinger, D. 2000. *NASA Engineering Network – Lessons Learned; Entry 0913; Space Mechanisms Reliability.* http://www.nasa.gov/offices/oce/IIis/0913.html

[2] Harper, A. 2005. *General Environmental Verification Standard (GEVS) for Goddard Flight Programs and Projects*. GEVS-STD-7000. NASA Goddard Space Flight Center, Greenbelt, Maryland

[3] Bedingfield, K.L. and Leach, R.D. 1996. *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment.* Ed. Alexander, M.B. National Aeronautics and Space Administration, Huntsville, Alabama

[4] Sarfield, Liam P. 1998. *The Cosmos on a Shoestring; Small Spacecraft for Space and Earth Science*: *Appendix B; Failure In Spacecraft Systems*. Rand Corporation, Santa Monica, California

[5] Newell, J and Oberhettinger, D. 2000. *NASA Engineering Network – Lessons Learned; Entry 0913; Space Mechanisms Reliability.* http://www.nasa.gov/offices/oce/IIis/0913.html

[6] Sarfield, Liam P. 1998. *The Cosmos on a Shoestring; Small Spacecraft for Space and Earth Science*: *Appendix B; Failure In Spacecraft Systems*. Rand Corporation, Santa Monica, California

[7] Sarfield, Liam P. 1998. *The Cosmos on a Shoestring; Small Spacecraft for Space and Earth Science*: *Appendix B; Failure In Spacecraft Systems*. Rand Corporation, Santa Monica, California

[8] Sarfield, Liam P. 1998. *The Cosmos on a Shoestring; Small Spacecraft for Space and Earth Science*: *Appendix B; Failure In Spacecraft Systems*. Rand Corporation, Santa Monica, California

[9] Sarfield, Liam P. 1998. *The Cosmos on a Shoestring; Small Spacecraft for Space and Earth Science*: *Appendix B; Failure In Spacecraft Systems*. Rand Corporation, Santa Monica, California

[10] Rules for the Design, Development, Verification and Operation of Flight Systems, GSFC-STD-1000. http://gsfcrules.gsfc.nasa.gov/ December, 2006

[11]Oberhettinger, David. 2002. *NASA Engineering Network – Lessons Learned; Entry 1196; Test as You Fly, Fly as You Test, and Demonstrate Margin.* http://www.nasa.gov/offices/oce/IIis/1196.html

[12] Sarafin, Thomas P. and Larson, Wiley J. 1995 *Spacecraft Structures and Mechanisms.* Pgs. 38-56. Microcosm Inc., Torrance California

[13] Harper, A. 2005. *General Environmental Verification Standard (GEVS) for Goddard Flight Programs and Projects*. GEVS-STD-7000. NASA Goddard Space Flight Center, Greenbelt, Maryland

[14] Issoupov, V and Startsev, O.V. et all. 2004. Combined Effect of Thermal and Mechanical Stresses on the Viscoelastic Properties of a Composite Material for Space Structures, in *Space Technology Proceedings, Volume 5, pgs 271-280.* Springer, Netherlands

[15] Rules for the Design, Development, Verification and Operation of Flight Systems, GSFC-STD-1000. http://gsfcrules.gsfc.nasa.gov/ December, 2006

[16] *he National Academies Press.* 1996. Accelerated Aging of Materials and Structures: The Effects of Long-Term Elevated Temperature Exposure; Degradation Mechanisms. National Academy of Sciences, Washington, D.C

[17] Issoupov, V and Startsev, O.V. et all. 2004. Combined Effect of Thermal and Mechanical Stresses on the Viscoelastic Properties of a Composite Material for Space Structures, in *Space Technology Proceedings, Volume 5, pgs 271-280.* Springer, Netherlands

[18] Sarafin, Thomas P. and Larson, Wiley J. 1995 *Spacecraft Structures and Mechanisms.* Pgs. 38-56. Microcosm Inc., Torrance California

[19] Sarafin, Thomas P. and Larson, Wiley J. 1995 *Spacecraft Structures and Mechanisms.* Pgs. 38-56. Microcosm Inc., Torrance California

[20] Sarafin, Thomas P. and Larson, Wiley J. 1995 *Spacecraft Structures and Mechanisms.* Pgs. 38-56. Microcosm Inc., Torrance California

[21] Sarafin, Thomas P. and Larson, Wiley J. 1995 *Spacecraft Structures and Mechanisms.* Pgs. 38-56. Microcosm Inc., Torrance California
[22] The James Webb Space Telescope Home Page. NASA.