Internal NASA Study: NASA's Protoflight Research Initiative

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Executive Summary

The NASA Protoflight Research Initiative is an internal NASA study conducted within the Office of the Chief Engineer to better understand the use of Protoflight within NASA. Extensive literature reviews and interviews with key NASA members with experience in both robotic and human spaceflight missions has resulted in three main conclusions and two observations. The first conclusion is that NASA's Protoflight method is not considered to be "prescriptive." The current policies and guidance allows each Program/Project to tailor the Protoflight approach to better meet their needs, goals and objectives. Second, Risk Management plays a key role in implementation of the Protoflight approach. Any deviations from full qualification will be based on the level of acceptable risk with guidance found in NPR 8705.4. Finally, over the past decade (2004 – 2014) only 6% of NASA's Protoflight missions and 6% of NASA's Full qualification missions experienced a publicly disclosed mission failure. In other words, the data indicates that the Protoflight approach, in and of it itself, does not increase the mission risk of in-flight failure. The first observation is that it would be beneficial to document the decision making process on the implementation and use of Protoflight. The second observation is that If a Project/Program chooses to use the Protoflight approach with relevant heritage, it is extremely important that the Program/Project Manager ensures that the current project's requirements falls within the heritage design, component, instrument and/or subsystem's requirements for both the planned and operational use, and that the documentation of the relevant heritage is comprehensive, sufficient and the decision well documented. To further benefit/inform this study, a recommendation to perform a deep dive into 30 missions with accessible data on their testing/verification methodology and decision process to research the differences between Protoflight and Full Qualification missions' Design Requirements and Verification & Validation (V&V) (without any impact or special request directly to the project).

Introduction

The NASA Protoflight Research Initiative is an internal NASA study conducted within the Office of the Chief Engineer to better understand the use of Protoflight within NASA. NASA has been using the term Protoflight since Goddard Space Flight Center (GSFC) coined the term in the 1960's to "avoid overrunning budget limitations" along with other factors. The first designated Protoflight spacecraft was launched in November 1965 and was called the Direct Measurements Explorer (DME-A). According to the first General Environmental Test Specification for Spacecraft and Components (GSFC S-320-G-1) published in 1969, a Protoflight spacecraft was defined as "(1) either a spacecraft originally designated as a prototype and subjected to complete or partial design qualification environmental testing, and then designated for flight use or (2) a spacecraft designated in advance to serve both as a prototype and a flight model." [1] Today's definition, located in the General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects (GSFC-STD-7000A), defines Protoflight as "flight hardware of a new design; it is subject to a qualification test program that combines elements of prototype and flight acceptance verification; that is, the application of design qualification test levels and flight acceptance test durations."

While the definitions of Protoflight have not varied much in the past 50 years, the use of Protoflight has significantly increased. From 1965-1974, a total of 16 Protoflight spacecraft were launched compared to a total of 49 Protoflight missions launched from 2004-2014. The increased use of the Protoflight approach for larger more complex spacecraft, subsystems and instruments causes one to ask the question, does using the Protoflight approach increase the likelihood of mission failures?

To answer this question and others, the authors of this paper conducted an extensive literature review encompassing the current policy and standards used within NASA, the number and type of NASA missions flown in the past 20 years and the number of missions that were exclusively Protoflight or that used one or more Protoflight subsystems/instruments in the past 10 years. Given the vast amounts of information regarding this topic and the various deep dives that could take place, the authors restricted the research to three areas each with a stated purpose to properly scope the literature review. The three areas and their purpose are as follows:

1. Conduct a literary review of the current Policy and Standards at the Agency and Center levels for Protoflight programs and projects within NASA. Other US Agencies, foreign space programs, and companies' policies/procedures/standards regarding Protoflight are not actively sought in this review. The purpose of the literary review is to understand what policies/standards are in place at the Agency and Center levels with a focus on when the Protoflight model began being used and the current guidance on the use of Protoflight models versus a full qualification model.

2. Collect and analyze data on NASA's flight missions and projects that have flown in the past 10 years using the Protoflight methodology at the payload, subsystem and/or instrument level. The purpose of this data retrieval and analysis is to understand the program/project's decision to use the Protoflight approach and the rate of failure (partial

and/or full) tracing back to a reduced life time expectancy of the payload/subsystem/instrument due to the use of the Protoflight methodology.

3. Characterize the level of Protoflight verification and Risk Management techniques used by NASA's Protoflight missions/projects that have flown in the past 20 years. The purpose of this characterization is to determine the various implementations of the Protoflight approach used in NASA's Protoflight missions/projects and the effect of the Protoflight approach used on Risk Management (technical and programmatic).

Current Protoflight Guidance

An extensive literature review was conducted to locate and obtain NASA's Agency and Center level documentation regarding Protoflight qualification standards, requirements, policies, and guidance. Public and non-public sources were used to locate documentation. Non-NASA documentation was not actively sought, however if non-NASA documentation was located and obtained it was included in this study. Table 1 shows the various documents obtained including the document number, title, published and expiration date (where applicable) and the responsible center/organization. The documents obtained cover a broad range of information regarding the Protoflight method including design levels, qualification levels for Protoflight, Prototype/Qualification and Acceptance, NASA policy regarding Risk Classification and the use of the Protoflight approach verification test requirements/matrix, see Table 2.

Table 1. A list of the obtained NASA’s Agency and Center level Protoflight and/or ProtoQual Qualification Documentation including a Non-NASA sourced Department of Defense (DoD) Handbook including all applicable dates and responsible Center.

Document No.	Title	Published	Expires	Center
GSFC-STD-7000 REV A	General Environmental Verification Standard (GEVS) for Flight Programs and Projects	4/22/2013		GSFC
APR-8070.2	Class D Spacecraft Design and Environmental Test	9/17/2008	9/17/2013	ARC
MSFC-HDBK-670	General Environmental Test Guidelines (GETG) for Protoflight instruments and experiments	6/1/1991		MSFC
NASA-STD-7002A	Payload Test Requirements	9/10/2004		HQ
NASA-STD-7003A	Pyroshock Test Criteria	12/20/2011		HQ
NASA-STD-7001A	Payload Vibroacoustic Test Criteria	1/20/2011		HQ
NASA-STD-5001B	Structural Design and Test Factors of Safety for Spaceflight Hardware	8/6/2014		HQ
NPR 8705.4	Risk Classification for NASA Payloads (Updated w/change 3)	6/14/2004	6/14/2018	HQ
DOD-HDBK-343 (USAF)	Design, Construction and testing requirements for one of a kind Space Equipment	2/1/1986		DOD
JSC-65828 REV A	Structural Design Requirements and Factors for Spaceflight Hardware for Human Spaceflight	10/1/2011		JSC
SSP 41172 REV U	Qualification and Acceptance Environmental Test Requirements ISS Program	3/28/2003		JSC
JPL Rules! DocID 55833 Rev 1	Spacecraft System Dynamic and Static Testing, Rev. 1	4/15/2013		JPL
JPL	System Thermal Testing, Rev. 2	5/8/2013		JPL

Table 2. A list of the obtained NASA's Agency and Center level Protoflight Qualification Documentation including a Non-NASA sourced Department of Defense (DoD) Handbook including the subject matter covered in the document. (Yes means the topic was covered in the document, No means the topic was not covered in the document)

Document No.	Title	Protoflight approach (policy)	Design Levels	Verification Test Requirements/ Matrix	Prototype/Qual Levels	Protoflight Levels	Acceptance Levels	Structural Loads (level & duration)	Acoustics (level & duration)	Random Vibe (level & duration)	Sine Vibe (level & duration)	Mech Shock (actual & sim)	Therm-Vac (Max/Min)	Thermal Cycling (Max/Min)	EMC & Magnetics	Contamination Control	End to End Testing
GSFC-STD-7000 REV A	General Environmental Verification Standard (GEVS) for Flight Programs and Projects	None / Goddard Std Approach	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
APR-8070.2	Class D Spacecraft Design and Environmental Test		Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MSFC-HDBK-670	General Environmental Test Guidelines (GETG) for Protoflight instruments and experiments		No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NASA-STD-7002A	Payload Test Requirements		No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No
NASA-STD-7003A	Pyroshock Test Criteria		No	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No
NASA-STD-7001A	Payload Vibroacoustic Test Criteria		No	No	No	Yes	Yes	No	Yes	Yes	No	No	No	No	No	No	No
NASA-STD-5001B	Structural Design and Test Factors of Safety for Spaceflight Hardware		Yes	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No
NPR 8705.4	Risk Classification for NASA Payloads (Updated w/change 3)	Policy governing the use of the Protoflight approach based on Risk Class	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
DOD-HDBK-343 (USAF)	Design, Construction and testing requirements for one of a kind Space Equipment		No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No
JSC-65828 REV A	Structural Design Requirements and Factors for Spaceflight Hardware for Human Spaceflight		Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No
SSP 41172 REV U	Qualification and Acceptance Environmental Test Requirements ISS Program		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
JPL Rules! DocID 55833 Rev 1	Spacecraft System Dynamic and Static Testing, Rev. 1	None / JPL Std Approach	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
	System Thermal Testing, Rev. 2	None	Yes	No	No	No	No	No	No	No	No	No	Yes	Yes	No	No	No

The majority of the documents obtained give guidance in the form of technical standards, requirements, design criteria and/or test criteria without programmatic guidance. Some of the documents are NASA standards that pertain to specific technical areas such as pyro shocks and vibro acoustics. Others are aligned with the General Environmental Verification Standard (GEVS) for Flight Programs and Projects, GSFC-STD-7000, which covers a broad range of technical information. There is one key difference between the GEVS and other Center's Protoflight documentation based on the GEVS. The GEVS states "The standard is written in accordance with the current GSFC practice of using a single Protoflight payload for both qualification testing and space flight… The Protoflight verification program, therefore, is given as the nominal test program." In other words, Full Qualification is the exception and no longer the norm at Goddard Space Flight Center (GSFC).

Only one document attempts to give guidance regarding the use of Protoflight through "recommended requirements" based on risk classification, NPR 8705.4 Risk Classification for NASA Payloads. NPR 8705.4 Appendix C - Recommended SMA-Related Program Requirements for NASA Class A-D Payloads, states the level of rigor recommended to qualify flight payloads characterized with a Class A, B, C or D risk classification. Currently GSFC and JPL use the Protoflight verification program as the nominal approach for non-heritage flight payloads with a risk classification of Class B – D, which agrees with the "recommended" requirements in NPR 8705.4 Appendix C. For missions with a risk classification of Class A NPR 8705.4 states "Full formal qualification and acceptance test programs and integrated end-to-end testing at all hardware and software levels." However, the requirement is only "recommended" and does not require a waiver if a program/project does not comply. For an example, Mars Science Laboratory (MSL) a Category 1, Risk Class A Robotic Mission used the Protoflight approach on specific subsystems/instruments but not the entire payload. While a waiver was not required, the decision to use the Protoflight approach was acknowledged in MSL's Key Decision Point (KDP) documentation.

The Protoflight method within NASA is not considered to be "prescriptive." The current policies and guidance allows each Program/Project to tailor the Protoflight approach to better meet their needs, goals and objectives. For example, some projects/missions use Engineering Test Units (ETUs) to test various subsystems/instruments prior to building the Protoflight Unit while others do not. Another example of variations between Protoflight projects is the decision to test or to use analysis to verify requirements during the qualification process. The decision process regarding the various implementation options of the Protoflight approach is based on several factors such as the heritage of subsystems/instruments, budget, schedule and risk posture of the project. The decision process is not required to be documented only agreed to by the decision making authorities.

Protoflight Mission Failures in the Past 10 and 20 years

Over the past 20 years, NASA has launched 215 missions varying from Category 3 Risk Class D missions all of the way to Category 1 Class A missions to Mars and launching humans into Lower Earth Orbit (LEO). Information regarding NASA's missions over the last 20 years was gathered and reviewed for any links to the use of the Protoflight methodology at the spacecraft, payload, subsystem, and/or instrument level. In some cases, information was not readily available for review. If enough information was not accessible the mission was noted as such. All accessible mission related documentation was reviewed for the following information:

- Mission Risk Classification
- Qualification Method used (Protoflight, Full Qualification)
- Launch Date
- Current Phase (Operating, Operating/Extended, Past, Past/Extended
- Government Agency and NASA Center involved
- Why the Protoflight approach was chosen
    - Information regarding this question was not available

With the following definitions for clarification:

> Operating Phase: A period of time in which the operational activities are carried out to meet the goals of the mission (Operational Phase)
>
> Operating/Extended Phase: A period of time after the planned operational activities have been carried out and additional operational activities are being carried out (Extended Operational Phase)
>
> Past Phase: The period of time after the mission has been decommissioned according to plan or because of a significant failure and without the mission entering into an Extended Operational Phase
>
> Past/Extended Phase: The period of time after the mission has been decommissioned the mission entering into an Extended Operational Phase

The authors categorized a mission's qualification method as Protoflight only if all of the below Protoflight criteria were met.

Protoflight Criteria

1. Mission spacecraft, subsystems and/or instruments were launched and operated in space

   - For STS missions, the only missions included are those that are external and fixed to the ISS or that are released into space
2. A known Protoflight qualified spacecraft hub, payload, subsystem and/or instrument is on board
   - If specific spacecraft, subsystem, or instrument information is unavailable but Risk Mission Class is known to be B, C, or D, the mission is automatically assumed to be Protoflight based on NPR 8705.4 Appendix C
     - Class A missions are automatically assumed to have gone through Full Qualification based on NPR 8705.4 Appendix C
3. The above criteria must have valid references, which include:
   - NASA personnel who worked the mission communicating via a face to face meeting, telephone call or email
   - NASA published (internal or external) documentation (NASA website, NASA Case Study, NASA Lessons Learned and/or NASA personnel author of a scientific/engineering journal article)

Once a complete list of all of NASA's missions over the past 20 years was collected and documented, the launch date, current phase, risk classification, qualification method and Government Agency/Center involved was determined through literature reviews of public and private accessible documentation. Documentation regarding the risk classification and qualification method used was not readily accessible for missions launched between 1994 and 2004, resulting in a data set too small for high fidelity analysis. While a large amount of information regarding NASA missions from 1994 – 2004 was inaccessible, the data that was collected is included for the reader's edification. Information regarding launched NASA missions during the last 10 years, 2004 through 2014, was readily available and allowed for a large enough set of information for analysis. For an example, Table 3 shows the total number of missions launched from 1994 – 2014 as 215 missions with only 110 missions having enough accessible information to determine the qualification method used. In the last decade alone, 2004-2014, 83 out of the 84 NASA missions launched had enough accessible information to determine the qualification method used. Table 4 is an example of the collected mission information.

Information on the launched Protoflight missions within the last 20 years (1994-2014) was collected and reviewed for mission failures with and without direct links to the Protoflight qualification method. In this paper and in accordance with NPR 8621.1B NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping, a "NASA mishap is an unplanned event that results in NASA Mission Failure before the scheduled completion of the planned primary mission. Where a NASA Mission Failure is a mishap of whatever intrinsic severity that prevents the achievement of the mission's minimum success criteria or minimum mission objectives as described in the mission operations report or equivalent document. (Note: A mission failure applies only to a NASA program's mission, and not a test or ongoing institutional operation. If a program accomplishes all minimum success criteria but not "full mission objectives," it is not a mission failure (even though in some cases it may appropriately be classified and investigated as a close call).” If a mission failure occurred a Failure Review Board (FRB) and/or Mishap Investigation Board (MIB) was created and a report released describing the failure/mishap and known and/or suspected cause. These reports were used to determine if a mission failure/mishap occurred on a Protoflight mission and the origin of said failure/mishap. If a mishap was found to occur on a Protoflight mission the data was collected and the report reviewed to determine any links to the Protoflight qualification method. When a mission failure/mishap occurred during an “Extended Operations” phase, the mission failure/mishap was not counted and the mission is only considered to be a “Past (extended) Mission.” Table 3 shows that there were 20 mission failures for missions launched from 1994 – 2014 with only 5 of those mission failures on missions launched in the past decade (2004-2014).

Table 3. Overview of Mission information collected for NASA Missions launched from 1994 – 2014 and 2004 – 2014 including Protoflight (PF) and Full Qualification Mission information and mission failures.

Launch Date	# All Mission	# All Missions w/ Risk Class or Protoflight information	#Operating Missions (Not Extended)	#Past Missions (Not Extended)	#Extended Past Missions	#Extended operating Missions	#All PF Missions (Operating, Past, Extended)	#Operating PF Missions (Not Extended)	#Past PF Missions (Not Extended)	#Past Extended PF Mission	#Operating Extended PF Missions	#Mission Failures	#PF Mission Failures	Known PF Linked Failures
1994 - 2014	215	110	36	73	19	41	69	16	17	8	28	20	5	0
2004-2014	84	83	24	32	5	23	50	16	12	3	19	5	3	0

Table 4. Example of Mission information collected for NASA Missions launched from 1994 – 2014 including Protoflight and Full Qualification subsystem information, risk mission classification, launch dates, current phase and responsible government agency and or NASA Center.

Mission Name	Mission Class	Protoflight systems	Proto-Qual Systems	Non-Protoflight systems	Unsure Systems	Launch Date	Current Phase	Government Agency/Center
JUNO	A					8/5/2011	Operating	NASA JPL
Gravity Recovery and Interior Laboratory (GRAIL)	C				LGRS	9/10/2011	Operating	NASA JPL
Suomi NPP	B				ATMS	10/28/2011	Operating	NASA GSFC
MSL	A				MMRTG	11/26/2011	Operating / Extended	NASA JPL / GSFC
NuSTAR	C/D					6/13/2012	Operating / Extended	NASA JPL / NASA GSFC
RBSP (Van Allen Probes)	C	EFW				8/30/2012	Operating	Johns Hopkins University APL
TDRS-K	A					1/30/2013	Operating	NOAA / NASA GSFC
LDCM Landsat 8	B	LDCM				2/11/2013	Operating	NASA GSFC / US geological Survey
IRIS	C/D	Spacecraft				6/26/2013	Operating	NASA GSFC / ARC
LADEE	C/D	Spacecraft				9/6/2013	Past	NASA ARC
MAVEN	B			Solar Arrays		11/18/2013	Operating	NASA GSFC / CU-LASP / SSL
TDRS-L	A					1/23/2014	Operating	NOAA / NASA GSFC
Global Precipitation Measurement (GPM)	B	Dual-frequency Precipitation Radar (DPR)				2/27/2014	Operating	JAXA / NASA GSFC
OCO-2	C			Spacecraft		7/2/2014	Operating	NASA JPL
Orion EFT-1		EFT-1				12/5/2014	Past	NASA

Protoflight Mission Failures between 2004 – 2014

Over the past decade, NASA has launched a total of 84 missions. All but one mission had enough accessible information to determine the flight qualification method used. 50 out of the 83 missions are classified as Protoflight qualified missions according to the assumptions made in the Protoflight Criteria discussed previously. In other words, 60% of NASA's missions in the past decade have had at least one Protoflight subsystem and/or instrument on board. This is a significant increase in the use of the Protoflight method compared to a study completed in 1975 that documented 16 out of the 55 missions (or 29%) over a similar time period were Protoflight. [1] Today, 35 of the 50 Protoflight missions are operational (16 Operating Phase and 19 Operating/Extended Phase) while, 15 Protoflight mission are no longer operational (12 Past Phase and 3 Past/Extended Phase), Table 3.

Only 5 missions over the past decade publicly reported a mission failure. Of the 5 reported, 3 occurred on Protoflight missions. In other words, 6% of the Protoflight missions (3 out of 50) and 6% of the Full qualification missions (2 out of 33) over the past decade have experienced a publically reported mission failure, Table 3. To better understand if there is a link between the Protoflight qualification method and a reported Protoflight mission failure, the 3 Protoflight missions (Glory, OCO and DART) that reported a mission failure were reviewed.

In 2011, the Glory satellite was lost in a launch vehicle failure when the payload fairing of the Taurus XL T9 launch vehicle failed to separate during ascent according to the Taurus XL T9 Mission Glory Mishap Investigation Board (MIB). [2] In 2009, the Orbiting Carbon Observatory (OCO) mission was lost in a launch vehicle failure when the payload fairing of the Taurus launch vehicle failed to separate during ascent according to the OCO Mishap Investigation Board (MIB). [3] In 2005, Demonstration of Autonomous Rendezvous Technology (DART) collided with the MUBLCOM satellite it was attempting to rendezvous with using completely autonomous maneuvers. The collision was found to be caused by inaccurate navigation system performance by the DART MIB. [4] None of the three payload mission failures were linked to the payload's Protoflight qualification method.

In conclusion, the data indicates that the Protoflight approach, in and of it itself, does not increase the mission risk of in-flight failure. This conclusion is in agreement with a previously reported study conducted in 1975 on Protoflight Spacecraft. [1]

Protoflight Mission Failures between 1994 – 2014

Documentation regarding the risk classification and qualification method used was not readily accessible for missions launched between 1994 and 2004, resulting in a **data set that is neither comprehensive nor sufficient.** While a large amount of information regarding NASA missions from 1994 – 2004 was inaccessible, the data is included for the reader's edification only.

Over the past two decades, NASA has launched a total of 215 missions. Approximately half of the launched missions (110 missions) had enough accessible information to determine the flight qualification method used. 69 out of the 110 missions are classified as Protoflight qualified missions according to the assumptions made in the Protoflight Criteria previously discussed. Today, 44 Protoflight missions are operational (16 Operating Phase and 28 Operating/Extended Phase) while 25 Protoflight mission are no longer operational (17 Past Phase and 8 Past/Extended Phase), see Table 3. Of the 17 Past Protoflight missions, only 5 Protoflight missions had a mission failure reported and published (Glory, OCO, DART, WIRE, ICESat). (Note: While the ICESat instrument laser failure was not classified as a NASA Mission Mishap, the failure is being included in the Protoflight mission failures due to the nature of the instrument laser failure and for the reader's edification.)

Information regarding Glory, OCO and DART can be found in the previous section. In 1999, the Wide-Field Infrared Explorer (WIRE) was declared a loss only 4 days after launch. The WIRE MIB determined that the root cause of the mission failure was due to a digital logic design error in the instrument pyro electronics box that caused the release of the telescope cover earlier than planned. The report stated that this error may have been caught during the acceptance/qualification testing if the test was allowed. However, the mission did not acquire enough pyros to test this function. [5] While none of the four previously mentioned Protoflight payload mission failures were linked to the payload's Protoflight qualification method, the ICESat GLAS laser failure can be debated if the failure is linked to the Protoflight qualification method.

ICESat was successfully launched in January 2003. On March 29, 2003, operating day 36, the Geoscience Laser Altimeter System's (GLAS) Laser 1 (out of three) unexpectedly stopped emitting. The laser failure resulted in the formulation of the Independent GLAS Anomaly Review Board (IGARB) to better understand the failure and to optimize science return. The laser failure resulted in a modified operating plan, with an approximate 30 day operation period (campaign), three times per year. This meant that the GLAS duty cycle was reduced from 100% to 27% per year. [6] To account for the modified operating plan, the science measurement campaigns were re-planned, and resumed in September 2003 using Laser 2. Even with the failure of Laser 1 and the reduced duty cycle of GLAS, the mission was successful and was granted a 2.5 year extension in 2005. After seven years of service, ICESat was decommissioned in August 2010. While the Laser 1 failure resulted in significant re-planning, the mission requirements were met and the mission ultimately was successful. [7]

The IGARB reported several findings that relate to the Protoflight qualification approach and to the use of heritage and COTS parts. Below are excerpts from the IGARB Executive Summary. [8]

1. "It is likely that the same problem that affected Laser 1 may also exist in Lasers 2 and 3. … Laser 1 operated for approximately 74 days of pre-launch operations plus 36 days of on-orbit operations. Lasers 2 & 3 pre-launch operations were 44 & 37 days, respectively."
2. "The potential problem …had not been uncovered during GLAS ground testing. The GLAS Instrument used a standard Protoflight qualification regime, which included thermal-vacuum and vibration environmental tests. Also, an Engineering Test Unit (ETU) had been constructed and tested, and accelerated life tests were successfully performed on similar

laser diode arrays. The detrimental effect of indium contamination is the major factor that had not been anticipated, detected, or accounted for. Laser 3 and the Engineering Test Unit (ETU) had experienced catastrophic failures of diode arrays during ground testing that had been analyzed and repaired with part replacement. Failure analyses conducted at the time had not uncovered the gold indide issues, and concluded that the likelihood of failure reoccurrence was extremely rare. Also, Lasers 1 and 3 had experienced small power output drops during unit level testing that were believed to be diode bar shunts. …The GLAS design incorporated extra diode arrays to allow for the darkening of individual bars by shunts."

3. "The GLAS laser diode arrays are complex, high technology and high performance assemblies that were procured as Commercial Off the Shelf (COTS) products for spaceflight applications. … The IGARB also concluded that hardware designated as having heritage from previous flight missions requires a rigorous analysis to ensure that it is the same as previously used and that it meets the requirements of the new mission. Heritage cannot be applied when there is a general lack of knowledge of the fabrication and assembly process, which is the general case for COTS products and the GLAS laser diodes in particular."
4. "It was noted by the Project that a significant factor in the anomaly was that GLAS was developed as Class C instrument, with Grade 3 parts (utilize manufacturer's processes and controls)."

Excerpts 1 and 2 from the IGARB Executive Summary are related to the Protoflight qualification approach. In regards to excerpt 1, a report documenting the total time that Laser 1, 2 and 3 were operated was not available and thus no conclusions can be drawn from the differences in pre-launch laser operation durations and the potential effects. Excerpt 2 states that the GLAS followed the standard Protoflight qualification regime including thermal-vacuum and vibration environmental testing and the failure mode was not detected during this testing. Failures and anomalies did occur on GLAS's ETU. However, the failure analysis in regards to the GLAS ETU pointed to different failure modes than those found by the IGARB on the Protoflight GLAS. Excerpt 3 and 4 from the IGARB Executive Summary are related to heritage COTS parts. The Protoflight qualification method does not state weather or not heritage and/or COTS parts can be used and therefore the decision to use heritage and/or COTS parts is not directly linked to the Protoflight method.

The authors do not attempt to draw any conclusions from this set of incomplete data. This section was provided for the reader's edification and may be used in the future as a starting point for further analysis and review.

Discussion

The use of the Protoflight method is widely accepted and successful within NASA's flight projects spanning from small Category 3 Class D missions all of the way to Category 1 Class A robotic missions. In fact over the past decade only 6% of the Protoflight missions (3 out of 50) and 6% of the Full qualification missions (2 out of 33) have experienced a publically reported mission failure. The low number of mission failures is a result of the Agency and several Centers creating and implementing standards and requirements regarding the testing criteria of Protoflight qualified subsystems, instruments, payloads and spacecraft based off of the first General Environmental Test Specification for Spacecraft and Components (GSFC S-320-G-1) published in 1969. These documents have provided NASA Programs/Projects with accepted Protoflight qualification test criteria and design margins to ensure successful missions.

However none of the documents reviewed attempt to address the implementation of the Protoflight method. For an example, none of the documents reviewed address the following areas:

- Relevant heritage of components, instruments, subsystems, etc.
- Complexity of the mission
- Multiple units
- Documenting the decision process for the above items as well as the use of Protoflight in terms of the technical, cost, schedule and risk requirements

One document addresses the link between risk classification (acceptable risk/risk tolerance) and the Protoflight method, NPR 8705.4 Risk Classification for NASA Payloads. Risk classification establishes the acceptable risk associated with a program or project which has a direct impact on the implementation of the Protoflight method. "1.3.1 With the acceptable risk classification level established, using Appendix C as the guideline, the project can define and apply the appropriate design and management controls, systems engineering processes, mission assurance requirements, and risk management processes…" [9] The Risk Management approach taken by the Program/Project effects the implementation of the Protoflight method throughout the Life Cycle of the project. Program/Project Managers often strike a balance between technical risk mitigation and maintaining cost and schedule commitments. For an example, depending on the risk classification, budget, schedule, and heritage one project may or may not use an Engineering Test Unit (referred to as an Engineering Model in NPR 8705.4). The authors draw attention to counter an engineering culture that seeks to minimize risk by suggesting that it is always more appropriate to manage risk, than minimize it. To quote Charlie Bolden, "Put another way, **risk intolerance is a guarantee of failure to accomplish anything of significance."** [10]

Variations in the implementation of the Protoflight method have caused some to define another term, ProtoQual. Some have used this term interchangeably with Protoflight while others believe that there is a difference between the two terms. Given the definition of the term Protoflight and the various acceptable Protoflight implementations, <u>any qualification method that does not meet Full Qualification</u> (meaning 2 nearly if not identical units are built and tested, the 1st called the prototype to Qualification levels and durations and the 2nd called the flight unit to Acceptance levels and durations) <u>is considered Protoflight</u>. To better understand how Protoflight is viewed, the current uses and issues of Protoflight, and the decision making process to use Protoflight within NASA, the authors interviewed key NASA members with experience in robotic and human rated programs/projects.

Key NASA members mostly agreed on all topics that were discussed in the interviews. The first was that the Protoflight Method (at the spacecraft, payload, subsystem, and/or instrument level) is accepted throughout NASA for robotic missions (including Risk Class A Category 1 robotic missions) with the understanding that some missions may wish to perform Full Qualification given the risk posture of the Program/Project. In other words, Protoflight is considered a good engineering practice supported by analyses and precedent. To paraphrase one NASA civil servant, using Protoflight seems very logical when you blend risk, schedule, cost and technical. For Programs/Projects that have high risk and high criticality payloads/subsystems/instruments, Full Qualification should be considered. Second was the decision making process on the implementation and use of Protoflight should be documented. Typically the decision to go to Protoflight is typically not documented well if at all. If the decision to use the Protoflight method is documented, the documentation typically does not cover why Protoflight was chosen in regards to the overall risk posture, the implementation strategy used such as using an ETU or not, the varies decisions regarding the qualification compliance matrix, nor does it cover the current environment in which the decision was made. All parties agreed that the documentation of this decision would be extremely difficult for one main reason. The implementation of Protoflight can vary throughout the lifecycle due to unforeseen issues such as budget cuts, technical and schedule issues. For an example, originally a subsystem may start off as Full Qualification but due to schedule and technical issues within the project the subsystem switches to use the qualification unit as the flight unit making the subsystem Protoflight. Another example, is that the project may start off as Protoflight but due to increased public visibility the project may switch to Full Qualification.

The appropriateness of Protoflight and the implementation of Protoflight was discussed. The authors found that there is no general rule of thumb of when or how a Program/Project should use the Protoflight method. The lack of a “prescriptive” Protoflight approach is accepted and allows for each Program/Project to openly discuss/debate the various Protoflight implementations. Some of the debates circle around the following questions:

- Should a Project use the Protoflight Method for the 1st unit in a multiple unit mission?
- When should a Project use the Protoflight Method without an ETU?
- Should the Category 1 Class A mission use Protoflight subsystems/instruments if relevant heritage exists?
- What relevant heritage is required to ensure it meets this Program/Project requirements?
- Should the Project reduce design requirements on a Protoflight unit to save mass and cost?
- Should a Protoflight Project use the “Building Block design” for qualification (i.e. not a single unit used to qualify the entire system, qualified at various levels and over various units)?
- Should a Program/Project use the Protoflight Method (payload, subsystem, instrument level) on human spaceflight missions that are not multiple units? That are multiple units?

Many of these questions have been answered by previous missions however no project is the same and with the lack of documentation describing the rationale behind the decision, it is difficult to understand a previous mission’s applicability.

The decision making process to use Protoflight, the method of Protoflight implementation and the qualification methods selected in the compliance matrix is extremely beneficial for the Program/Project. During this process the complexity, heritage, cost, schedule, and risk are all discussed with respect to one another resulting in an increased shared knowledge of the Program/Project. This process helps to draw out the natural tension between maximizing the science and mitigating risks while maintaining schedule and budget. One of the main issues expressed with this process is the over estimation of relevant heritage designs, components, instruments and subsystems. For an example, if an instrument is thought to have substantial relevant heritage the instrument may follow the Protoflight path to minimize cost and schedule. However, if the relevant heritage was over stated and did not meet the projects requirements such as maximum and minimum operating temperatures, substantial rework may be necessary causing a slip in the schedule and an increase in cost. The over estimation of the relevant heritage on a project is common and leads to rework and in some cases redesigns of key components ultimately causing cost and schedule issues within the project. A Project/Program that chooses to use the Protoflight approach with relevant heritage, it is extremely important that the Program/Project Manager ensures that the current project's requirements falls within the heritage design, component, instrument and/or subsystem's requirements and that the documentation of the relevant heritage is comprehensive and sufficient.

Conclusion

The NASA Protoflight Research Initiative is an internal NASA study conducted within the Office of the Chief Engineer to better understand the use of Protoflight within NASA. Extensive literature reviews and interviews with key NASA members with experience in both robotic and human spaceflight missions has resulted in three main conclusions and two observations. The first conclusion is that NASA's Protoflight method is not considered to be "prescriptive." The current policies and guidance allows each Program/Project to tailor the Protoflight approach to better meet their needs, goals and objectives. NASA's current approach to allow each Program/Project to implement the Protoflight method based on the Program/Project's requirements is largely accepted and cherished. Due to NASA's approach, there are many ways to implement the Protoflight method depending on the relevant heritage, robotic or human spaceflight, multiple units, risk posture, budget, schedule, technical advancements, and environment. Second, Risk Management plays a key role in implementation of the Protoflight approach. Given that Risk Management is finding an acceptable level of risk (risk mitigation vs cost/schedule), any deviations from full qualification will be based on the level of acceptable risk with guidance found in NPR 8705.4. Finally, over the past decade (2004 – 2014) only 6% of NASA's Protoflight missions and 6% of NASA's Full qualification missions experienced a publicly disclosed mission failure. In other words, the data indicates that the Protoflight approach, in and of it itself, does not increase the mission risk of in-flight failure. The first observation is that it would be beneficial to document the decision making process on the implementation and use of Protoflight. The second observation is that If a Project/Program chooses to use the Protoflight approach with relevant heritage, it is extremely important that the Program/Project Manager ensures that the current project's requirements falls within the heritage design, component, instrument and/or subsystem's requirements for both the planned and operational use, and that the documentation of the relevant heritage is comprehensive, sufficient and the decision well documented. To further benefit/inform this study, a recommendation to perform a deep dive into 30 missions with accessible data on their testing/verification methodology and decision process to research the differences between Protoflight and Full Qualification missions' Design Requirements and Verification & Validation (V&V) (without any impact or special request directly to the project).

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