QUALIFICATION OF REUSABLE COMPONENTS FOR LAUNCH VEHICLES

Michael O'Malley
Environments & Launch Approval Branch
NASA Launch Services Program
John F. Kennedy Space Center, Florida

ABSTRACT

With the advent of launch vehicles being recovered after a mission with the goal of reuse for multiple missions, Qualification and Acceptance of already flown components is becoming a real concern. Besides a brief mention in MIL-HDBK-340A, a literature search for Government standards, handbooks or specifications to provide guidance for this issue finds little material. A procedure for qualification and flight acceptance of reusable components for multiple mission launch vehicles will be presented.

INTRODUCTION

With the advent of launch vehicles being recovered after a mission with the goal of reuse for multiple missions, Qualification and Acceptance of already flown components is becoming a real concern. A literature search for Government standards, handbooks or specifications to provide guidance for this issue finds little material. The topic is briefly mentioned in MIL-HDBK-340[1]:

"Reusable space vehicle hardware consists of the space vehicles and components intended for repeated space missions. Airborne support equipment and space vehicles, which perform their missions while attached to a recoverable launch vehicle, are candidates for reuse, particularly for multiple mission programs. The reusable equipment would be subjected to repeated exposure to test, launch, flight, and recovery environments throughout its service life. The accumulated exposure time of space vehicles retained in the recoverable launch vehicle and of airborne support equipment is a function of the planned number of missions involving this equipment and the retest requirements between missions.

Airborne support equipment environmental exposure time is further dependent on whether or not its use is required during the acceptance testing of each space vehicle. In any case, the service life of reusable hardware should include all planned reuses and all planned retesting between uses.

The testing requirements for reusable space hardware after the completion of a mission and prior to its reuse on a subsequent mission depends heavily upon the design of the reusable item and the allowable program risk. Based on present approaches, it is expected that the retrieved space vehicle would be returned to the contractor's factory for disassembly, physical inspection, and refurbishment. All originally specified acceptance tests should be conducted before reuse.

It is important to note that reentry, while not normally a mission phase for single-use flight equipment, may impose a set of environmental test conditions for reusable flight equipment. An example would be the inclusion of reentry deceleration in an acceleration test of a payload intended for multiple missions. The qualification test requirements for reusable flight equipment can be derived by the logical extension of the methodology contained in MIL-STD-1540B."

This white paper will develop a procedure for qualification and flight acceptance of reusable components for multiple mission launch vehicles. First, a review of Qualification and flight Acceptance of expendable launch vehicles will be discussed followed by the new procedure for reusable components.

REQUIREMENTS REVIEW OF QUALIFICATION AND FLIGHT ACCEPTANCE OF EXPENDABLE LAUNCH VEHICLES [2,3,4,5]

Space vehicle hardware are subjected to extreme environments during launch and operational life. A method to insure good reliability with acceptable risk to mission success has led the industry to subject space vehicle hardware to extensive ground testing.

The purposes of thermal tests are twofold.

First, environmental stress screening tests are designed to detect design flaws, material, process and workmanship defects in space vehicle hardware by subjecting the component to an environment where the temperature is cycled between hot and cold extremes more severe than the one expected in actual usage, thereby subjecting the hardware to extreme thermal stresses. These thermal stresses force flaws that are not ordinarily apparent into observable failures. These flaws are latent defects that could cause premature component failure. Defects can include loose connections, broken wire bonds, defective solder joints, inadequate stress relief, performance drift, bent connector pins, defective or contaminated parts, thermal-coefficient-of-expansion mismatches, and material deficiencies. When these flaws are discovered, they are repaired, or problem equipment is replaced prior to flight. In thermal testing, the test temperature, the number of test cycles, and the rate of temperature change are parameters that establish the efficiency of environmental stress screening.

Second, they demonstrate the capability of the part to function at temperature extremes that include substantial margin to that which will be expected during flight. Performance verification is accomplished through functional tests conducted prior to, during, and after environmental tests.

Two levels of testing are used.

Qualification Tests

To demonstrate that the design meets specification requirements or to expose design defects, the qualification environment exposes the qualification hardware to the most extreme flight environments conditions, more severe than expected during the operational life of the flight hardware. Because of the severity of this environment, qualification hardware is not flown.
The number of qualification thermal cycles is intended to demonstrate a capability for 4 times the thermal fatigue potentially expended in service life. The requirements assume that such fatigue is dominated by acceptance testing, and that the flight and other aspects (such as transportation) do not impose significant additional fatigue. It includes as many as 2 times the number of thermal cycles specified for acceptance testing and retesting.
Qualification tests also validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software. The test item is produced from the same drawings that are used for production of the flight hardware. Its production uses the same materials, tooling, manufacturing processes, and level of personnel competency as are used for production of the flight hardware.

The unit is considered LSP Qualified if it meets the requirements covered in Launch Services Program document ENGINEERING REVIEW PROCESS (ERP) LSP-P-321.01 Revision A:

7.1 Qualification Status

*A component or subsystem is considered "qualified" if it has been tested, analyzed, demonstrated, or shown by similarity to meet all functional requirements and demonstrate margin over all expected, storage, shipping, handling, flight, and acceptance environments. Qualification must be accomplished against a documented standard (e.g. **MIL-STD-1540B** or **NASA-STD-7009**).*

Acceptance Tests

Formal acceptance tests demonstrate the acceptability of a deliverable item. Acceptance tests provide quality-control assurance by acting as an environmental stress screen to precipitate incipient failures resulting from latent defects in parts, materials, and workmanship and to verify conformance to specification requirements. These tests, which are conducted after qualification testing, prove the flightworthiness of the article.

Thermal Cycling and Thermal Vacuum Tests

Thermal testing of units consists of thermal cycling and thermal vacuum testing. Thermal cycling subjects a unit to rapidly changing hot and cold temperatures in an ambient (atmospheric pressure) environment, with the primary objective of environmental stress screening and workmanship verification. Thermal vacuum testing subjects a unit to hot and cold temperature cycles in a vacuum environment with the primary objective of performance verification. Thermal cycling is recognized as the most effective screening environment for detecting unit-level failures, whereas the thermal vacuum test simulates the most realistic flight environment in ground testing. A thermal vacuum test (TVAC) detects defects that would respond only to a vacuum environment such as corona/arcing and multipaction, plus potential materials outgassing problems.

QUALIFICATION MARGIN AND THE EQUIVALENT ACCEPTANCE THERMAL CYCLE

Each time an electronic circuit heats up and cools down, thermal gradients create thermal stress, which then creates fatigue on all the solder joints on the board. As previously mentioned, the number of qualification thermal cycles is intended to demonstrate a capability for 4 times the thermal fatigue potentially expended in service life. For single use expendable launch vehicles, the service life is assumed to be dominated by acceptance testing. The qualification unit must have experienced the same thermal fatigue as what would be experienced as a result of four acceptance tests. The difference in thermal fatigue the qualification unit experienced compared to the flight unit is the margin that provides confidence the flight unit will perform successfully. Because there are many different ways a qualification unit can be thermally tested and many ways a flight unit can be thermal cycled, a method is needed to be able to convert the various thermal cycles to a common form and sum the total as a measurement of thermal fatigue. One method is introduced in MIL-STD-1540C[6] in Table VI where this equation is in note 5.

Eqn (1)

$$N_Q = 4N_{AMAX} \left(\frac{\Delta T_A}{\Delta T_Q}\right)^{1.4}$$

Where:

N_Q= Required number of Qualification cycles

N_{AMAX}= Maximum allowable number of acceptance cycle, including Retesting

ΔT_A= Temperature range in Acceptance test

ΔT_Q= Temperature range in Qualification test

Using MIL-STD-1540B values of 85°C for the acceptance temperature range and 105°C for the qualification temperature range with 8 cycles for the number of acceptance cycles, results in 23.8 or rounded up, 24 required qualification cycles. In other words, the equation modifies the acceptance cycles into equivalent qualification cycles. Each acceptance cycle is equivalent to 0.744 qualification cycles because the temperature range in the acceptance test is smaller than in the qualification test. Each acceptance test subjects the unit to 5.95 equivalent qualification cycles. To meet requirements, the qualification unit must have experienced the equivalent of four acceptance tests which is 4x5.95=23.8. The acceptance test cycles must be converted to equivalent qualification cycle to arrive at a stress equivalence.

The above equation is just another form of the Coffin-Manson equation.

COFFIN-MANSON EQUATION [7,8,9]

The number of thermal cycles needed to initiate a crack is a function of the strain amplitude, which in turn depends on the magnitude of the temperature change during the thermal cycle. Once the crack is initiated, it propagates during subsequent thermal cycles.

The Coffin-Manson equation models the effects of such low-cycle fatigue induced by thermal stressing. It follows an Inverse Power Law relationship. That is, as the magnitude of induced stress increases, the number of cycles to failure decreases by a constant power. The equation developed from research done by L.F. Coffin Jr. and S.S. Manson is as follows:

Eqn (2)
$$N_f = C_1\left(\Delta\varepsilon_p\right)^{-C_2} = \left(\frac{\Delta\varepsilon_p}{2\varepsilon_f}\right)^{-C_2}$$

Where:
N_f = Number of cycles to failure (cycles)
$\Delta\varepsilon_p$ = Plastic strain
ε_f = Strain at fracture
C_1 = Proportionality constant for the particular material
C_2 = 1/c where c is the strain ductility exponent

The plastic strain, $\Delta\varepsilon_p$, is proportional to the magnitude of thermal cycle temperature change, ΔT, or in other words, the ratio of the temperature range and the resulting plastic strain range in the solder joint $\Delta T/\Delta\varepsilon_p$, is assumed constant. Because of this, the preceding form of the Coffin-Manson equation may be rewritten in terms of the magnitude of the thermal cycle temperature change as follows:

Eqn (3) $$N_f = C_1(\Delta T)^m$$

Where:
N_f = Number of thermal cycles to failure (cycles)
ΔT = Magnitude of thermal cycle temperature change
C_1 = Proportionality constant for the particular material
m= Coffin-Manson exponent

The preceding form of the Coffin-Manson Model is seldom used as is. It is usually written in terms of an "acceleration factor", which compares thermal cycles in the more stressful test environment with thermal cycles in the use or flight environment. The expression shows how a greater temperature range in a thermal cycling test accelerates the fatigue that would happen to a unit in normal operation. Thermal cycles in the more stressful test environment are used to estimate the equivalent thermal cycles in the use or flight environment.

The Coffin-Manson Model written in terms of an "acceleration factor" for thermal cycles is as follows:

Eqn (4) $$AF = \frac{N_{fu}}{N_{fA}} = \left(\frac{\Delta T_A}{\Delta T_u}\right)^m$$

Where:
N_{fu} = Number of cycles to failure at use (flight) temperature change
N_{fA} = Number of cycles to failure at accelerated temperature change
ΔT_A = Thermal cycle temperature change in accelerated environment
ΔT_u = Thermal cycle temperature change in use (flight) environment
m = 1.4 to 2.65 for solder joints depending on solder material

The above equation gives you the equivalent cycles for the unit in normal operation based on the number of cycles the unit saw in the thermal cycling test. This relationship essentially provides an equivalence between thermal cycles with different ΔTs by changing the number of cycles. For the purposes of this effort, the equation is reversed so it gives the number of equivalent acceptance thermal cycles based on what the unit saw in other thermal cycle testing.

Eqn (5) $$N_{fA} = N_{fu}\left(\frac{\Delta T_u}{\Delta T_A}\right)^m$$

However, this assumes the ΔT is the same for all cycles in the thermal cycle test program. If the unit underwent thermal cycles with different ΔTs, such as a qualification unit that underwent acceptance test thermal cycles (ΔT=85°C) and then underwent qualification test thermal cycles (ΔT=105°C) a way is needed to sum up the cumulative effect of the thermal cycles. The stress can be summed using Miner's rule as discussed below. Once the total equivalent acceptance thermal cycles of the flight unit are summed, they are divided by the total equivalent acceptance thermal cycles the qualification unit experienced. This difference is an expression of life remaining.

MINER'S RULE [10,11]

In 1945, M. A. Miner popularized a rule that had first been proposed by A. Palmgren in 1924. The rule, variously called Miner's rule or the Palmgren-Miner linear damage hypothesis, states that where there are k different stress magnitudes in a cyclic stress spectrum, S_i $(1 \leq i \leq k)$, each contributing $n_i(S_i)$ cycles, then if $N_i(S_i)$ is the number of cycles to failure of a constant stress reversal S_i (determined by uni-axial fatigue tests), failure occurs when:

Eqn (6)
$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

Where:
n_i = Number of cycles accumulated at stress S_i
N_i = Number of cycles to failure
C = The fraction of life consumed by exposure to the cycles at the different stress levels. In general, when the damage fraction reaches 1, failure occurs.

Usually for design purposes, C is assumed to be 1. This can be thought of as assessing what proportion of life is consumed by a linear combination of stress reversals at varying magnitudes. Though Miner's rule is a useful approximation in many circumstances, it has major limitations. It fails to recognize the probabilistic nature of fatigue. The sequence in which high vs. low stress cycles are applied to a sample in fact affect the fatigue life, for which Miner's Rule does not account. However, since individual thermal cycles are kept identical in a thermal cycle test, the method does provide a good approximation of the total stress during the thermal cycling test.

CALCULATING LIFE REMAINING IN FLIGHT UNITS

In a flight unit that has had issues during it's' acceptance testing and possible repair leading to additional full or partial acceptance testing, a method is needed to calculate the remaining life as compared to the qualification unit.

The method is a combination of the Coffin-Manson equation and Miner's rule.

Eqn (7)
$$N_{fA} = N_{fui} \sum_{i=1}^{n} \left(\frac{\Delta T_{ui}}{\Delta T_A}\right)^m = N_{fu1} \left(\frac{\Delta T_{u1}}{\Delta T_A}\right)^m + N_{fu2} \left(\frac{\Delta T_{u2}}{\Delta T_A}\right)^m + \ldots + N_{fun} \left(\frac{\Delta T_{un}}{\Delta T_A}\right)^m$$

Where:
N_{fA} = Number of equivalent acceptance cycles
N_{fui} = Number of cycles at temperature change i
N_{fu1} = Number of cycles at temperature change 1

N_{fu2} = Number of cycles at temperature change 2
N_{fun} = Number of cycles at temperature change n
ΔT_{ui} = Thermal cycle temperature change in environment i
ΔT_{u1} = Thermal cycle temperature change in environment 1
ΔT_{u2} = Thermal cycle temperature change in environment 2
ΔT_{un} = Thermal cycle temperature change in environment n
ΔT_A = Thermal cycle temperature change in acceptance test environment
m = 1.4 to 2.65 for solder joints

An example illustrates the method. Assume the qualification unit had MIL-STD-1540 B acceptance and qualification thermal cycle and thermal vacuum testing. The total equivalent acceptance thermal cycles on the qualification unit would be:

Table 1: Equivalent Acceptance Cycles for the Qualification Unit

Qual Unit					Acceptance test ΔT
					85
Test	# of cycles	Low Temperature	High Temperature	ΔT	Coffin-Manson/ Miner's Rule
Acceptance Thermal Cycles	8	-24	61	85	8.00
Acceptance Thermal Vacuum Cycle	1	-24	61	85	1.00
Qualification thermal Cycles	24	-34	71	105	36.62
Qualification Thermal Vacuum Cycle	3	-34	71	105	4.58
Total	36				50.20

Now assume the flight unit had a problem during its first ATP where two cycles did not have the required ΔT, so two additional cycles had to be done. Then failures occurred that led to repair extensive enough to require another full ATP. During the second ATP a minor issue arose that required an extra modified ATP due to a repair. The total equivalent acceptance thermal cycles on the flight unit would be:

Table 2: Equivalent Acceptance Cycles for the Flight Unit

Flight Unit					Acceptance test ΔT
					85
Test	# of Cycles	Low Temperature	High Temperature	ΔT	Coffin-Manson/ Miner's Rule
Acceptance Thermal Cycles	6	-24	61	85	6.00
Acceptance Thermal Cycles (issue #1)	2	-20	55	75	1.56
Acceptance Thermal cycles	2	-24	61	85	2.00
Acceptance Thermal Vacuum cycle	1	-24	61	85	1.00
2nd test Acceptance thermal Cycles	8	-24	61	85	8.00
3rd test modified Acceptance Thermal Cycle	3	-24	61	85	3.00
Total	22				21.56

The flight unit would be acceptable because it has (1-21.56/50.20=0.57) 57% of its life left when compared to the qualification unit.

NORRIS-LANDZBERG EQUATION [12-22]

Researchers have found the Coffin-Manson Model to yield somewhat conservative estimates for fatigue life. IBM researchers K.C Norris and A.H. Landzberg modified it to compensate for frequency-dependent and time-dependent anomalies.
Norris and Landzberg proposed that plastic strain dominated thermo-mechanical fatigue of eutectic SnPb alloy, the primary solder of choice in electronic packaging at that time. In ignoring the influence of elastic strain, Norris-Landzberg, like Coffin-Manson, assumed that the plastic strain range is directly proportional to the temperature excursion range. This is expressed by the first term of the equation. Although developed for eutectic SnPb solder, the Norris-Landzberg model can be used for predicting the fatigue life of both tin/lead and lead-free solder joints.

To account for the influence of creep-driven plasticity and stress relaxation, Norris- Landzberg added additional correction factors based on temperature-cycling frequency and maximum temperature of the solder material. The model uses frequency to express the temperature ramp rates (cold to hot and hot to cold) and the dwell stages of the temperature cycling test profile. The frequency exponential "n" varies from 0 to 1, with value 0 for no frequency effect and 1 for the maximum effect depending on the materials and testing conditions. A value equal to 1/3 is commonly used to extrapolate the laboratory accelerated thermal cycles-to-failure data with short duration (high frequency) to on/off field operating cycles with long duration (low frequency).

The third term takes into account the effect of the maximum temperature between the use environment and the test environment by using the Arrhenius equation. The equation is:

Eqn (8)
$$AF = \frac{N_{fu}}{N_{fA}} = \left(\frac{\Delta T_A}{\Delta T_u}\right)^m \left(\frac{f_A}{f_u}\right)^n \left(e^{\frac{E_a}{k}\left(\frac{1}{T_u}-\frac{1}{T_A}\right)}\right)$$

Where:
N_{fu} = Number of cycles to failure at use (flight) temperature change (cycles)
N_{fA} = Number of cycles to failure at accelerated temperature change (cycles)
ΔT_A = Thermal cycle temperature change in accelerated environment (K)
ΔT_u = Thermal cycle temperature change in use environment (K)
f_A = Frequency of thermal cycles in accelerated environment (cycles/day)
f_u = Frequency of thermal cycles in use environment (cycles/day)
E_a = Activation energy, ≈0.122eV
k = Boltzmann's constant
T_u = Maximum UUT temperature in use environment (K)
T_A = Maximum UUT temperature in accelerated environment (K)
m = 1.4 to 2.65 for solder joints, 1.9 for SnPb eutectic solder
n = 1/3 for SnPb eutectic solder
Ea/k = 1414 for SnPb eutectic solder

The Norris-Landzberg equation has several key limitations when used to predict fatigue life. The equation is based on the assumption that creep behavior is driven exclusively by temperature and time. The change in applied stress at different thermal cycles could have a more substantive effect then identified through frequency and temperature, possibly changing rate constants depending on the solder joint configuration and overall packaging architecture. In addition, the equation is dependent upon the plastic strain being driven by the same mechanism in both environments. Plasticity and creep behaviors are dependent on the specific combination of temperature and applied stress. Finally, the stress-strain relationship can vary dramatically as the solder joint is exposed to a range of temperatures creating a hysteresis loop. Both Coffin-Manson and Norris-Landzberg assume no hysteresis.

Fortunately, for this application, these are not concerns because only a comparison to the qualification unit is being made to determine remaining life, not a total fatigue life calculation. The qualification and flight units are identical, so the solder joint configuration and packaging architecture are identical. Also, the temperature rise and fall rate and dwell time are usually very similar for the qualification and flight units.

Similar to what was done for the Coffin-Manson equation, for the purposes of this effort, the equation is reversed so it gives the number of equivalent acceptance thermal cycles based on what the unit saw in other thermal cycle testing.

Eqn (9)

$$N_{fA} = N_{fu}\left(\frac{\Delta T_u}{\Delta T_a}\right)^m \left(\frac{f_u}{f_A}\right)^n \left(e^{-\frac{E_a}{k}\left(\frac{1}{T_u}-\frac{1}{T_A}\right)}\right)$$

Moreover, as before, Miner's rule is used to sum the individual acceptance tests.

Eqn (10)

$$N_{fA} = N_{fui}\sum_{i=1}^{n}\left(\frac{\Delta T_{ui}}{\Delta T_A}\right)^m \left(\frac{f_{ui}}{f_A}\right)^n \left(e^{-\frac{E_a}{k}\left(\frac{1}{T_{ui}}-\frac{1}{T_A}\right)}\right)$$

Where:
N_{fA} = Number of equivalent acceptance cycles
N_{fui} = Number of cycles at temperature change i
ΔT_{ui} = Thermal cycle temperature change in environment i
ΔT_A = Thermal cycle temperature change in acceptance test environment
f_{ui} = Frequency of thermal cycles at any temperature change
f_A = Frequency of thermal cycles at standard acceptance temperature change
E_a = Activation energy, ≈0.122eV
k = Boltzmann's constant
T_{ui} = Maximum UUT temperature in in any thermal cycle (K)
T_A = Maximum UUT temperature in standard acceptance test (K)
m = 1.4 to 2.65 for solder joints, 1.9 for SnPb eutectic solder
n = 1/3 for SnPb eutectic solder

An example illustrates the method. Assume the same qualification unit as before with the cycle rise and fall rate at 3°C/minute and a 2-hour dwell at each temperature extreme, the same as the MIL-STD-1540 B acceptance test. The total equivalent acceptance thermal cycles on the qualification unit would be:

Table 3: Equivalent Acceptance Cycles for the Qualification Unit

Qual Unit			Acceptance Test High T, C	Acceptance Test ΔT, C	Acceptance Test ramp rate, C/min	Acceptance Test Dwell, hr		Cycle Frequency Standard ATP Cycles/hour		
			61	85	3	2		0.20		
Test	# of Cycles	Low Temp, C	High Temp, C	ΔT, C	Ramp Rate, C/min	Dwell, hr	Coffin-Manson	Frequency Ratio	Arrhenius Equation	Equivalent Acceptance Cycles
Acceptance Thermal Cycles	8	-24	61	85	3	2	1.00	1.00	1.00	8.00
Acceptance Thermal Vacuum Cycle	1	-24	61	85	3	2	1.00	1.00	1.00	1.00
Qualification Thermal Cycles	24	-34	71	105	3	2	1.53	0.99	1.13	40.81
Qualification Thermal Vacuum Cycle	3	-34	71	105	3	2	1.53	0.99	1.13	5.10
Total Cycles/Miner's Rule	36									54.91

Now assume the flight unit is the same as before except the second ATP and the modified ATP were accelerated to a ramp rate of 10°C/min and the dwell shortened to 1 hour to save time. The total equivalent acceptance thermal cycles on the flight unit would be:

Table 4: Equivalent Acceptance Cycles for the Flight Unit

Flight Unit			Acceptance Test High T, C	Acceptance Test ΔT, C	Acceptance Test ramp rate, C/min	Acceptance Test Dwell, hr		Cycle Frequency Standard ATP Cycles/hour		
			61	85	3	2		0.20		
Test	# of Cycles	Low Temp, C	High Temp, C	ΔT, C	Ramp Rate, C/min	Dwell, hr	Coffin-Manson	Frequency Ratio	Arrhenius Equation	Equivalent Acceptance Cycles
Acceptance Thermal Cycles	6	-24	61	85	3	2	1.00	1.00	1.00	6.00
Acceptance Thermal Cycles (Issue 1)	2	-20	55	75	3	2	0.78	1.01	0.93	1.45
Acceptance Thermal Cycles	2	-24	61	85	3	2	1.00	1.00	1.00	2.0
Acceptance Thermal Vacuum Cycle	1	-24	61	85	3	2	1.00	1.00	1.00	1.00
2nd Test Acceptance Thermal Cycles	8	-24	61	85	10	1	1.00	1.29	1.00	10.35
3rd Test modified Acceptance Thermal Cycles	3	-24	61	85	10	1	1.00	1.29	1.00	3.88
Total Cycles/Miner's Rule	22									24.68

The flight unit would be acceptable because it has (1-24.68/54.91=0.55) 55% of its life left when compared to the qualification unit.

QUALIFICATION AND FLIGHT ACCEPTANCE OF REUSABLE LAUNCH VEHICLES

The methods previously discussed are well suited to calculate the remaining life of reusable components. A more detailed look at the service life, however, is key to identifying possible sources of additional fatigue. The service life of an item starts at the completion of fabrication and continues through all acceptance testing, handling, storage, transportation, prelaunch testing, all phases of launch, possible orbital operations, disposal, reentry or recovery from orbit, refurbishment, retesting, and reuse that may be required or specified. Additional information, which probably is not presently recorded or known, on storage and transportation environments as well as full-scale vehicle tests and reentry environments will be needed to complete the assessment. It may result in further qualification tests to demonstrate the unit has margin, especially if a significant number of reuses are planned.

Assuming all the environment information begins to be recorded or thermal analysis is provided, remaining life predictions can be made. An example can illustrate the process. The same qualification unit is assumed as before with 55 equivalent thermal cycles. The assumptions made for the flight unit are as follows. The unit undergoes the typical acceptance test, is in storage for 3 months, is in transportation for two weeks, and has one full up booster firing test, one prelaunch vehicle firing test followed by flight and re-entry. Upon recovery, the unit is refurbished or repaired and has a truncated ATP of 3 cycles followed by the rest of the previous sequence. The table shows the flight unit could be used for 7 flights before its life is consumed when compared to the qualification unit. This indicates the qualification unit would need further testing if a life greater than 7 was planned. In the example, the storage time, transportation time, booster test, prelaunch vehicle firing, flight and re-entry environments were assumed identical for each cycle between refurbishment and flight. In the real application, these could be different. A table like the one presented could be included in the part's pedigree and updated after each flight to calculate the remaining life in comparison to the qualification unit before the next flight.

Table 5: Equivalent Acceptance Cycles for the Flight Unit

Flight Unit			Acceptance Test High T, C	Acceptance Test ΔT, C	Acceptance Test ramp rate, C/min	Acceptance Test Dwell, hr		Cycle Frequency Stnd ATP Cycles/hour		
			61	85	3	2		0.20		
Test	# of Cycles	Low Temp, C	High Temp, C	ΔT, C	Ramp Rate, C/min	Dwell, hr	Coffin-Manson	Frequency Ratio	Arrhenius Equation	Equivalent Acceptance Cycles
Acceptance Thermal Cycles	8	-24	61	85	3	2	1.00	1.00	1.00	8.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 1	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 2	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 3	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 4	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 5	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60

Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 6	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Re-entry	1	-14	51	65	0.7	1	0.58	0.99	0.88	0.58
Refurbishment or Repair	3	-24	61	85	3	2	1.00	1.00	1.00	3.00
Storage 3 months (1 cycl/day)	90	13	30	17	0.5	10	0.04	0.62	0.65	3.60
Transportation (1 cycle/day)	14	0	41	41	0.5	10	0.23	0.60	0.76	3.26
Booster test	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Pre-Launch Vehicle Test Fire	1	0	41	41	0.7	2	0.23	0.94	0.76	0.23
Launch 7	1	-14	51	65	0.7	2	0.58	0.89	0.88	0.58
Total Cycles/Miner's Rule	781									55.12

CONCLUSIONS AND RECOMMENDATIONS

The method presented here has been used for a number of years by the Launch Services Program to assure expendable space hardware flies with “baseline risk”. The use of the Norris-Landzberg method can be expanded to reusable space hardware if the additional information can be obtained describing the environment the component sees during its service life. Test and flight data combined with thermal analysis can provide the needed data. The only issues are the additional thermal analyses that needs to be done and the effort to maintain the data base in an expanded pedigree. Requalification of flight hardware may be necessary to achieve the desired flight lifetime.

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