U2 Rocket Catapult Mechanistic Aging and Surveillance Testing

Phase I – Disassembly, Chemistry, Preliminary Structural Analysis and Preliminary Service Life Estimate

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24 May 2016

Testing and Analysis

- Three motors received for dissection
  - 2008 Motor used for Full Test Matrix material properties initial service life estimate.
  - 2000 and 2004 Motors used to evaluate motor-to-motor variability and also obtain information on aging chemical mechanisms by 12-month storage at elevated temperatures.

Date of Manufacture	Age at Test
2008	7
2004	11
2000	15

Disassembly-Several Components

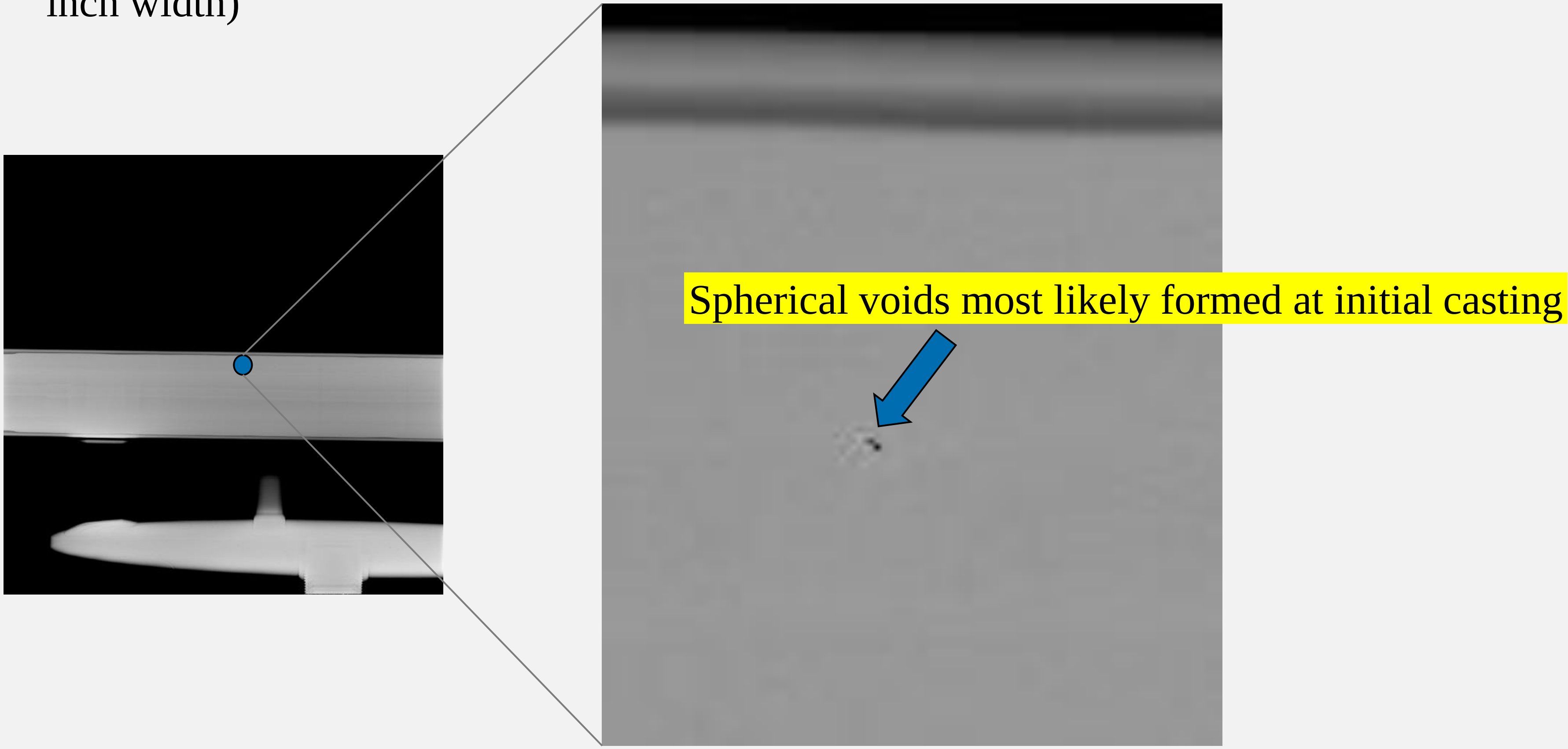
- Base Cartridge (Catapult motor)
  - Propellant
  - $BKNO_3$ pellets

- Head Cartridge
  - $BKNO_3$ pellets

- Main Cartridge
  - Main grain propellant

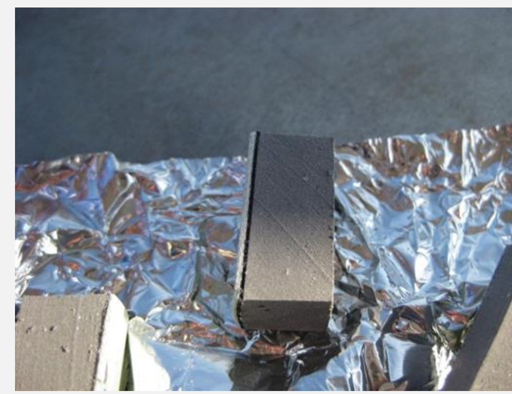
NDT Inspection

- No reportable Defects for 2000 and 2008 Motors
- 2004 Motor showed heavy and uneven liner throughout the motor with numerous voids in the propellant (Maximum dimension of voids: 0.136-inch length and 0.043-inch width)



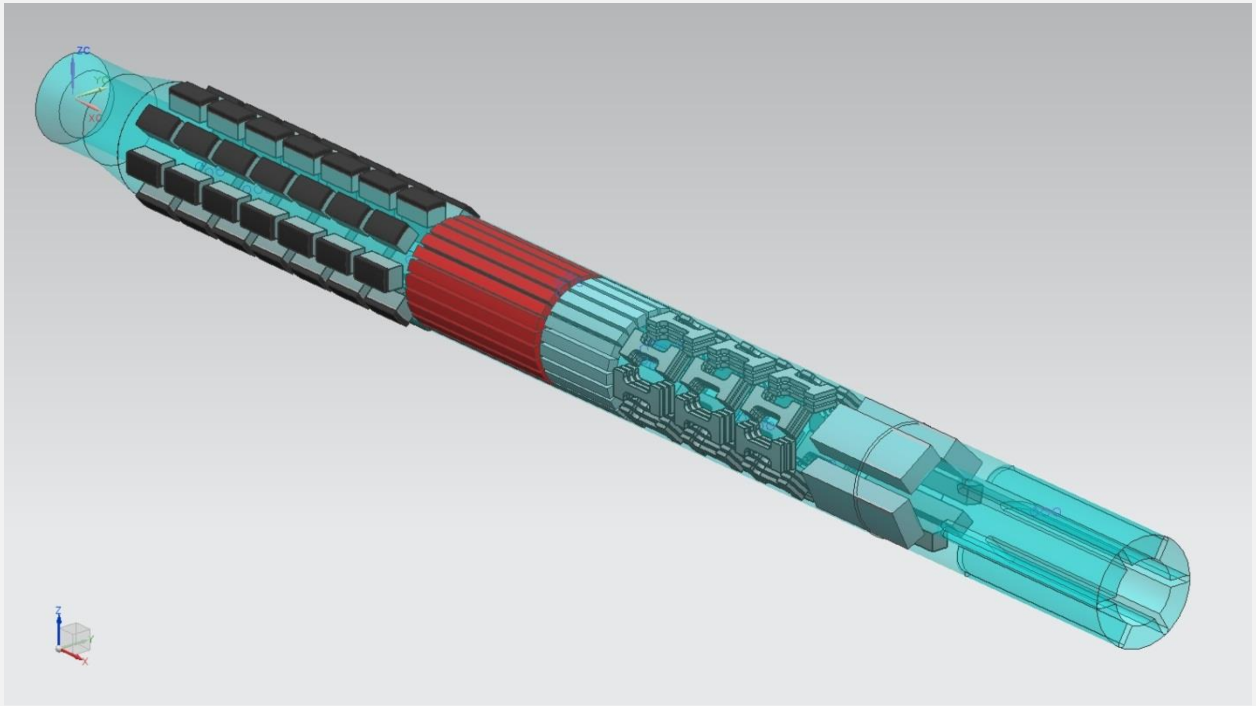
2008 Motor- Full Test Matrix

Test	Specimen	Pressure (psig)	Rate (in/min)	Strain (%)	Replicates at Temperature -65°F	-30°F	0°F	75°F	110°F	130°F	165°F
Uniaxial Tensile	mini-dogbone	0	0.01		-	-	3	3	-	3	3
		0	1		3	-	3	3	-	3	-
		1000	1		-	-	3	3	-	3	3
		1000	10		3	-	3	3	-	3	-
Birate	Mini-dogbone	0-1000	Pull to 10% strain at 0.01 ipm and 0°F, ambient psig, hold for 1 hour, pressurize to 1000 psig an pull to failure at 10 ipm. Do 3 replicates.								
Bond Tensile	mini-DPT	0	0.01		-	-	3	3	-	3	3
		0	1		3	-	3	3	-	3	
Bond Shear	mini lap shear	1000	1		-	-	3	3		3	3
		1000	10		3	-	3	3		3	
Relaxation Modulus	mini-prism	0		5%	3	3	3	3	3	3	3
Density		0	NA					3			
Shore A 10 second reading (Propellant)	Motor	0	NA					5			
~~Shore D 5 second reading~~	~~Phenolic Liner~~	~~0~~			~~5~~			~~5~~			~~5~~
~~Shore D 5 second reading~~	~~Forward Insulation~~	~~0~~			~~5~~			~~5~~			~~5~~
Burn Strand		5 pressures						3 each pressure			
Moisture Content		0						3			
HoE (heat of Explosion, DSC)											
Propellant CTE	3" x 0.4" x 0.4"	0	NA	0	3 replicates from -65°F to 200 °F						
Chemical	Microtome	0	NA		Profile (bondline to bore)						
Mechanical	Microtensile	0	0.01		75 °F Profile (bondline to bore)						
XLD	Microtome	0	NA		Profile (bondline to bore)						



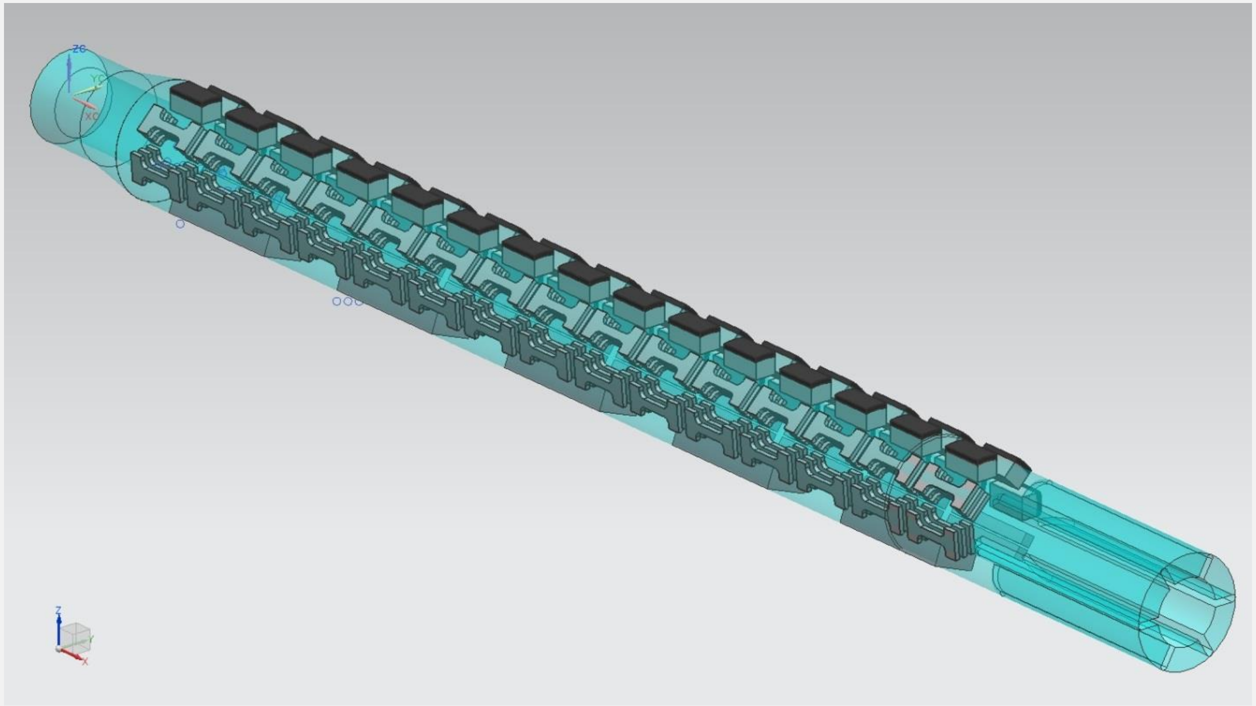
Main Grain 2008 Motor

Produce samples for full propellant characterization



2000 and 2004 Motor

Produce samples for reduced test matrix to document motor-to-motor variation and samples to be placed into aging to determine the affect of temperature and time on binder degradation mechanism.

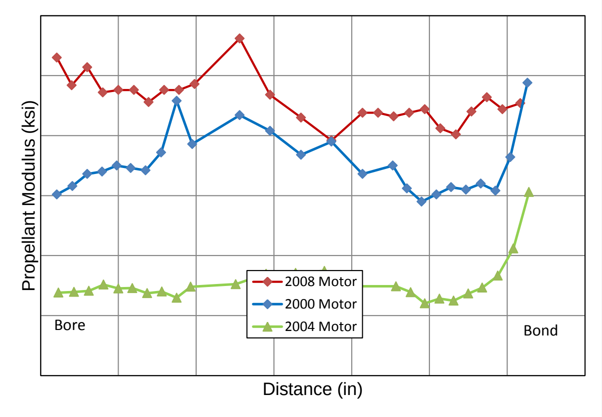


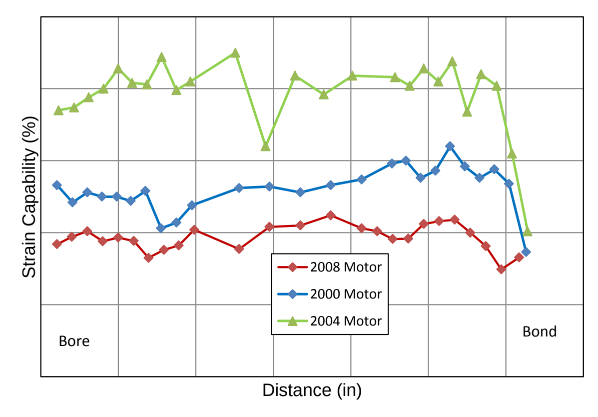
2000 and 2004 Reduced Test Matrix

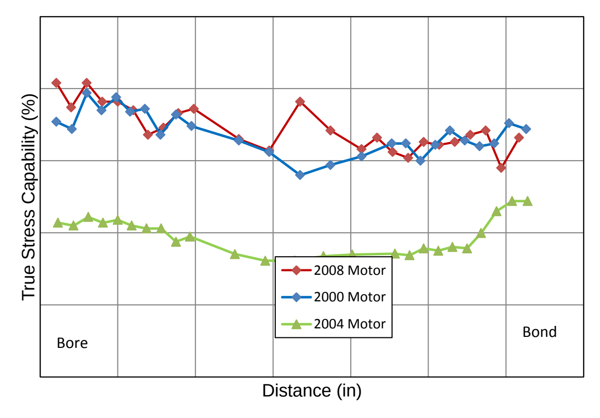
Test	Specimen	Pressure (psig)	Rate (in/min)	Strain (%)	Replicates at Temperature						
					-65°F	-30°F	0°F	75°F	110°F	130°F	165°F
Uniaxial Tensile	mini-dogbone	0	0.01				3	3			
		1000	10		-		3	3	-		-
Bond Tensile	mini-DPT										
		0	0.01		-	-		3	-		-
Bond Shear	mini lap shear										
		1000	10			-		3		-	-
Relaxation Modulus	mini-prism	0		5%	-			3			
Chemical	Microtome	Profile (bondline to bore)									
Mechanical	Microtensile	Profile (bondline to bore)									
XLD	Microtome	Profile (bondline to bore)									
Shore A 10 second reading	Slab	5 readings on slab at 75°F									

Motor Mechanical Properties Profile

- Hard layer is apparent at the 2004 and 2000 motor bondlines, but not in the 2008.
- 2004 Motor has softer properties compared to the other two motors.

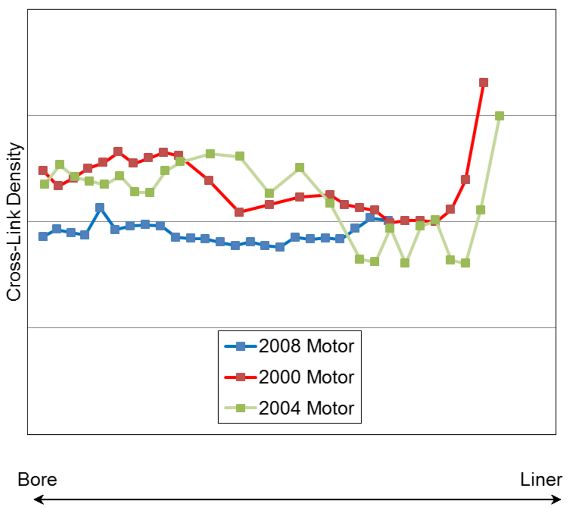




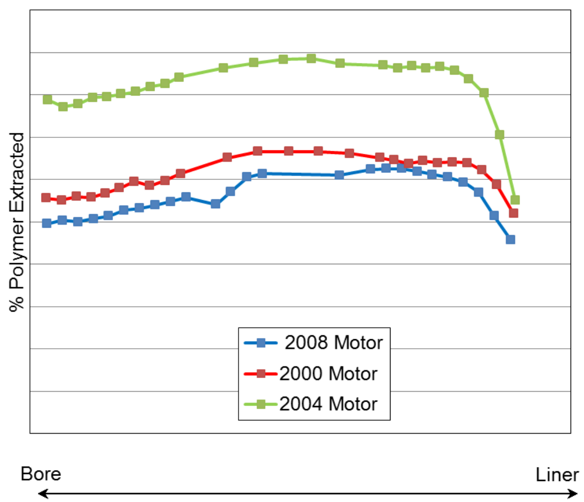


U2 Motors Profile---- Cross-link Density

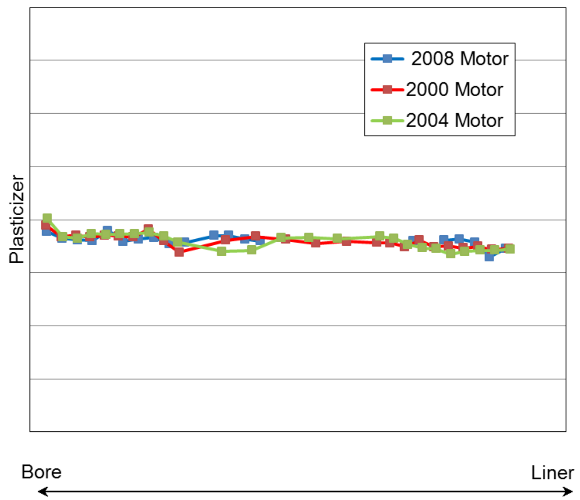
- Higher XLD at bond, expected lower 2004 XLD



- Less extractables near bondline. Extractable polymer higher for 2004 (as expected from modulus measurements)

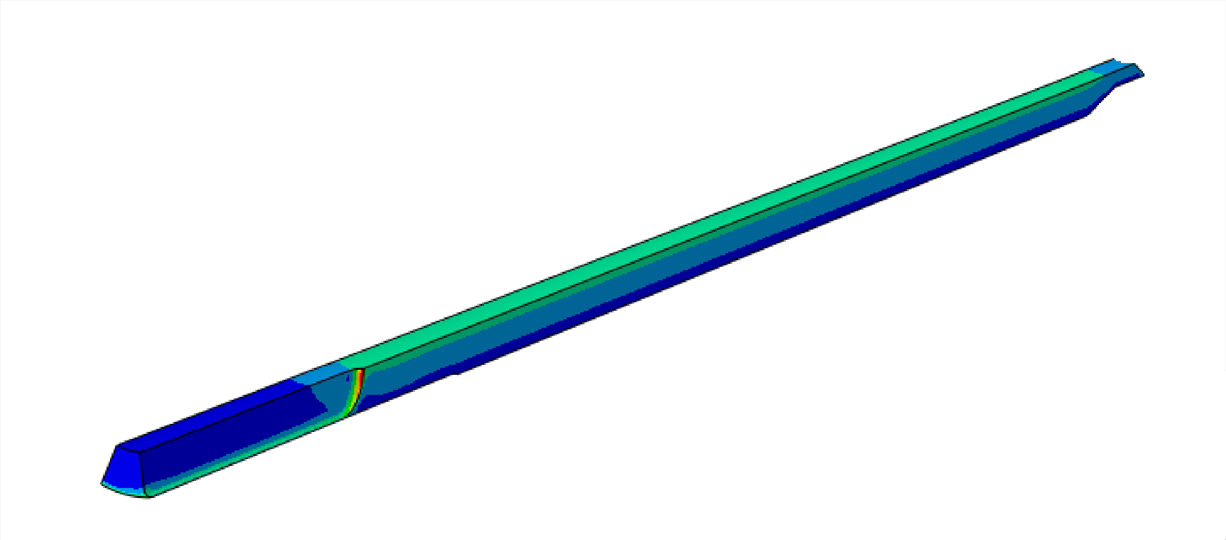


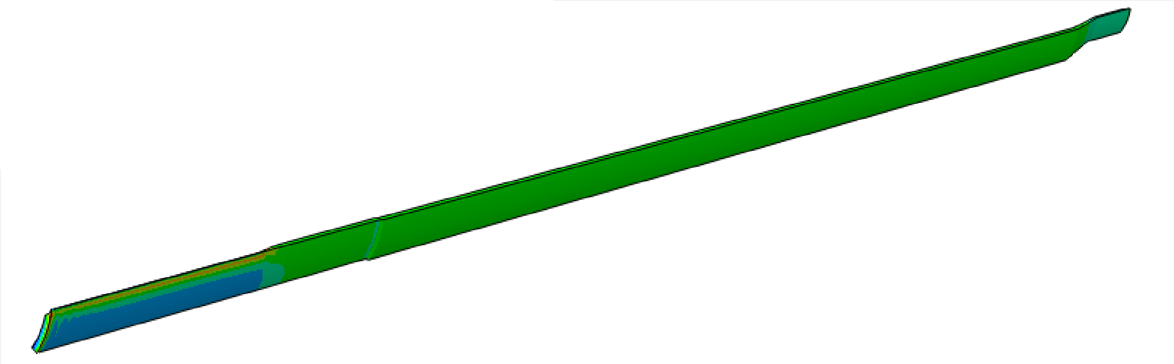
- Very consistent plasticizer levels for all motors, and no spatial gradient



Peak Stress/Strain Locations

- Peak grain strains and stresses at aft end of fin valley (near bore)
  - Persists for storage and ignition
- Peak grain-composite bond stresses at fin valleys





Storage FS (2000 and 2008 Motors)

Storage Propellant Bore Cracking

Temperature	FS
-65	3.87
-40	4.27
75	8.94
165	88.5

Softer 2004 propellant has higher FS

Storage Propellant-Composite Bond Tensile Failure

Temperature	FS
-65	1.40
-40	1.70
75	5.59
165	70

Ignition Margins (2000 and 2008 Motors)

Ignition Propellant Bore Cracking (Deviatoric Stress)

Temperature	FS
-65	1.13
-40	1.44
75	3.60
165	5.39

4500 psig
in 0.05 seconds

Softer 2004 propellant
has better FS

Ignition Propellant-Composite Bond Shear Failure

Temperature	FS
-65	1.74
-40	1.81
75	2.19
165	2.38

FEMCA

Material/ Component	Component Failure Mode	Factor of Safety	ASF	CF	FPF	System Effects
I. Propellant Structural						
	1) Bore crack initiation					
	a) High temperature (165 °F) storage	88	2	3	6	Catastrophic
	b) Low temperature (-65 °F) storage	3.9	2	3	6	Catastrophic
	c) High temperature(165 °F) operation	5.4	2	3	6	Catastrophic
	d) Low temperature (-65 °F) operation	1.1	2	1	2	Catastrophic
	2) Internal void crack propagation (2004 motor)					
	a) High temperature (165 °F) storage		2	2	4	Catastrophic
	b) Low temperature (-65 °F) storage		2	2	4	Catastrophic
	c) High temperature(165 °F) operation		2	2	4	Catastrophic
	d) Low temperature (-65 °F) operation		2	2	4	Catastrophic
II. Propellant Ballistics						
	1) Ballistic performance specification violation					
	a) High temperature operation		3	2	6	Catastrophic
	b) Low temperature operation		3	2	6	Catastrophic
III. Bondlines						
	1) Propellant-liner-case bond failure					
	a) High temperature (165 °F) storage	70	2	3	6	Catastrophic
	b) Low temperature (-65 °F) storage	1.4	2	1	2	Catastrophic
	c) High temperature (165 °F) operation	2.4	2	3	6	Catastrophic
	d) Low temperature (-65 °F) operation	1.7	2	2	4	Catastrophic
IV. Case (Steel)						
	1) Case burst (6000 psig)					
	a) High temperature operation	1.53	3	3	9	Catastrophic
	b) Low temperature operation	1.53	3	3	9	Catastrophic
	2) Case rupture due to internal heating, or burn-through		2	3	6	Catastrophic

Service Life Estimate

- **<u>Preliminary Service Life Estimate was provided</u>** based on similarity between 2000 and 2008 motor data and positive FS
  - Lowest FS = 1.1 for bore crack at for -65 °F operation (increases to 1.4 at -40°F)
  - 8 motors, 3-7 years old successfully static tested at -65 °F (IHTR 3152)
  - 2004 motor has improved (higher) FS due to lower modulus (lower induced stresses) and nominal stress capability (increased strain capability)
  - However internal voids in 2004 motor should be analyzed for crack propagation
  - Requires addition of fracture testing
- Aging study (in process) will identify and quantify aging behavior and allow a more accurate SLE with probability of failure for each failure mode

Phase I analysis has provided an improved SLE and significantly benefited the program