“¼ Scale” Ballistic Evaluation Motor (BEM)

4th Static firing report

Rev. 2007/01/28

Introduction

This Paper presents the test report detailing the fourth static firing of the "1/4 scale" Ballistic Evaluation Motor (BEM). Note that the ¼ scale refers to the scaling of the motor basic dimensions with respect to the planned full-scale motor for the *Sugar Shot to Space* project. This motor uses the same propellant type, but the construction details may differ significantly, especially with regard to materials used in the construction of the motor. The intent of the BEM testing is mainly to prove the "dual-phase" concept of operation, and to obtain performance data that will be used to aid the design of the full-scale motor.

The fourth test firing is essentially a repeat of the first three test firings which took place earlier this year. All three tests were partial successes – the first two suffering nearly identical problems, a ruptured casing during the second phase burn – the third test featured a successful 1st phase burn, followed by an "abort" when it was discovered that 2nd phase ignition failed due to inadvertent non-arming of the ignition system. This fourth test incorporates improvements to the propellant manufacturing, as well as use of a checklist to avoid oversights during preparation and arming.

Motor details

Details on the original design and construction of the BEM are outlined in the Technical Specifications Paper Rev. 2005/08/28. Due to the problem of thermal structural weakening of the casing during the 2nd phase burn that was experienced during the first two BEM tests, the design of the 1st phase casing was modified prior to the third BEM firing. Instead of using a length of EMT, a heavier-walled tubing of alloy steel was used. This particular tubing is seamless 4130 alloy with a 0.125 inch (3.12 mm) wall, with an OD of 3.00 inches (76.2 mm) and ID of 2.750 inches (69.85 mm). This modification was retained for the fourth firing.

Due to difficulties in removal of the bonded insulation liner from the first phase casing following the third firing (removal was needed due to some thermal degradation), it was decided not to re-install such a liner for the fourth test.

All other motor details are unchanged from the third BEM test.

As was the case for the 3rd BEM firing, thermal sensors were again mounted on the rocket motor casing. A total of eight sensors were used. However, the location of sensor #7 was changed, having been relocated from the aft region of the 1st phase casing to the nozzle throat. The intention of mounting a sensor on the throat was to have a time base datum point for the thermal data.

Instrumentation for collecting motor performance data was essentially the same as for the third BEM firing. Tandem loadcells (mounted "in series") were used once again for thrust measurement. Both loadcells were of the same type, MSI Sensors FC23 1000# button-type, calibrated by comparison to a factory calibrated Omega LC304-500 unit. Two pressure transducers were used to measure chamber pressure, one mounted at the forward bulkhead, used to measure 2nd phase pressure, and the other mounted at the mid-bulkhead, used to measure pressure of both firings.

<u>Propellant Grain</u>

The propellant grain consisted of a total of 12 segments, six for each phase. The six segments for the 2nd phase are the same ones that had been prepared for the third BEM firing, and were kept in sealed plastic bags for storage.

The potassium nitrate was veterinary grade of 99.8% purity and was milled using a coffee grinder to a fine powder form. The Sorbitol was *Now Foods* brand obtained from *PVCOnly.com* and was used as received. The weighed ingredients were prepared in 24 separate batches that were combined into sealed containers, and blended as a dry mix in a motorized rotating mixer for 3 hours per batch prior to casting.

These grains were prepared with Potassium Nitrate/Sorbitol (KNSB) propellant cast in the "standard" heat cast method in an Oxidizer/Fuel ratio of 65/35. A thermostatically controlled deep-fryer was used to heat the propellant to a slurry form for casting. The propellant was heated to a temperature of 135 ^{o}C. (275^{o} F), at which point it was cast. A vibrating table was used to help compact the slurry and to minimize air inclusion.

Propellant was cast into an inhibitor tube fabricated from "*Deltaflex 100*" heat-resistant gasket material. Just prior to casting, the tube was lined on the inside with a coating of melted sorbitol to aid in bonding the propellant to the tube material. After the propellant slurry was loaded into the tube, the propellant was "clamped" to squeeze out any trapped air. The casting tube with clamping apparatus is illustrated in Photo 1.

The faces of all segments were coated with ignition primer consisting of a blend of potassium nitrate, charcoal and a small percentage of sulfur. Coating was achieved by mixing the primer in 70% IPA and painting the slurry onto the propellant surface. The finished segments are illustrated in Photo 2

Propellant Summary for BEM firing #4:

	Do (in/mm)	Di (in/mm)	L (in/mm)	m (lb/g.)	Dc (in/mm)	Lc (in/mm)
	Diameter, grain	Core diameter	Length, grain	Mass per segment	Diameter, total	Length, total
1st phase	2.61 / 66.3	0.700 / 17.7	3.98 / 101	1.26 / 573	2.71 / 68.9	4.72 / 120
2nd phase	2.50 / 63.4	0.700 / 17.7	4.41 / 112	1.24 / 564	2.59 / 65.7	4.88 / 124

Phase one grain: 7.575 lb. (3439 g.)
Phase two grain: 7.449 lb. (3382 g.)

Phase one grain: Average density ratio was 96.4%
Phase two grain: Average density ratio was 94.6%

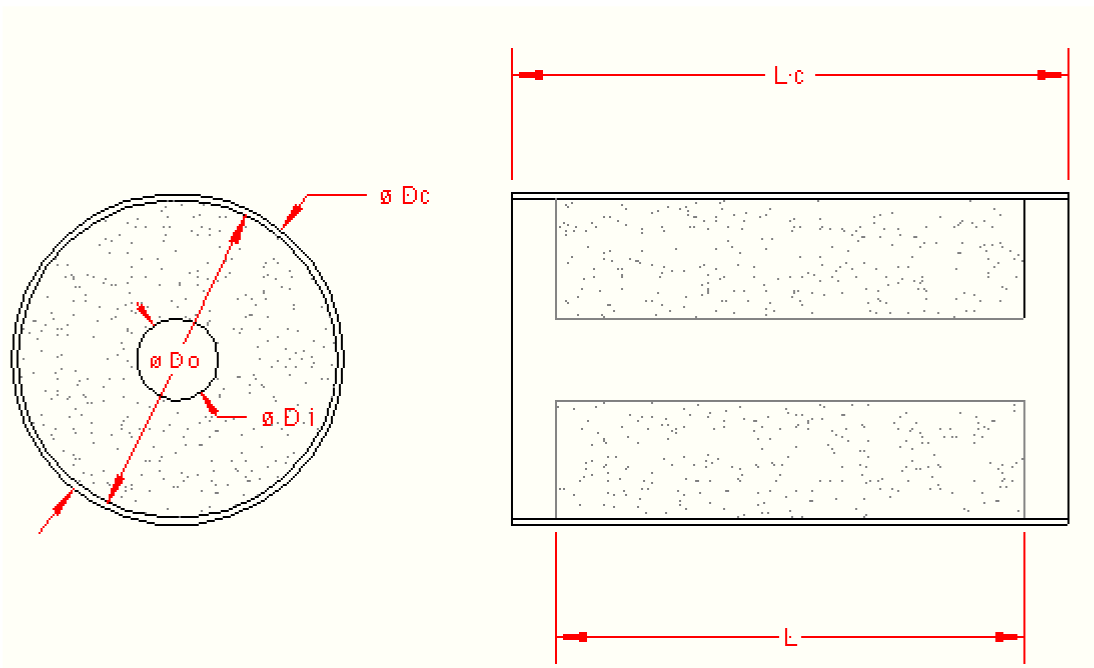

Figure 1 – Grain segment dimensions

The total length of the six segments was 4 inches (100 mm) shorter than the interior of the motor. As such, a tubular steel spacer was placed at the nozzle end in order to keep the grain segments in contact with one another.

Test Firing Report

September 23rd, 2006

Early in the morning of the planned firing date, Tarun Tuli, Daniel Faber and I headed to the test site, a two hour drive to the *Columbiad Commercial Test Range*. We arrived just after noon hour. After resting for a short while, we proceeded to begin setting up for the test firing. Richard Graf, of *Columbiad Launch Services*, gave us a welcome hand in setting up the test stand, instrumentation shelter and with mounting the rocket motor in the stand. Preparations went very smoothly, without any noteworthy glitches. The only snag was a malfunctioning FRS radio, one of three brought along for communication.

After setting up the equipment, the rocket motor was assembled, the tandem load cells mounted in the stand and confirmed to be functioning, the two pressure transducers were mounted on the motor, and the eight thermocouples attached at their assigned locations to the motor casing and nozzle. Following this, it was time to pull out the final checklist that had been prepared in order to help ensure all final preparations would go smoothly and without oversight. This involved doing a confirmation that both ignition systems were fully functional, that data acquisition was activated, as well as confirmation that the video recording cameras were adjusted and turned on. I did a last minute walk around of the motor to get visual confirmation that nothing obvious had been overlooked or was askew. Following this, the others left the vicinity and took up positions at the firing safety area, while I stayed behind to do the final connections of the igniters to the ignition boxes.

Following the checklist procedure, electrical continuity to both igniters was confirmed, and then both ARM switches were thrown from the SAFE position to the ARM position. I alerted the others over the FRS radio that both systems were being armed, and subsequently hurried to the safety area to join the others. I had taken on the duty of announcing the countdown and, using a stopwatch, tracking the time following burnout of the first phase. The second phase was to be fired 18 seconds later. Tarun was once again assigned the task of pressing the firing button for both phases. After confirming that all participants were ready, and that Tarun had turned the key to arm the firing button, I announced the countdown.

Five - 4 - 3 - 2 - 1 - fire! Immediately the motor roared to life, firing with an exceptionally loud shriek and sending a large white smoke plume well beyond the treetops, high into the air. The thrusting of the motor continued forcefully for about three seconds, then tailed off as the propellant was consumed. Black smoke could then be seen issuing from the nozzle from the burning delay plug and hot residue inside the motor. I pressed the "start" button on my stopwatch as soon as burnout occurred. When the stopwatch read "13" seconds of elapsed time, I began the second countdown: 5 - 4 -3 - 2 - 1 - fire! At this cue, Tarun pressed the second ignition button. After a brief moment, the motor once again awakened, roaring to life in much the same manner as it had moments earlier. The intensity of the sound was much the same, as was the burning duration. As the thrust tailed off and came to an end, accompanied by a weird, brief whistling sound, relief and awe silenced us all for but a moment. Then the cheers and hand-clapping of victory replaced the sudden silence, followed by hand-shakes all around.

The data acquisition systems for the thermocouples, load cells and pressure transducers once again worked well, and good data was collected.

A post-firing teardown of the motor showed it to be in excellent condition. Debris from the second phase grain inhibitor was found nested in the mid-bulkhead throat. This was likely the cause of the unusual whistling sound that was heard. Examination of the video showed a plume of black smoke that erupted briefly during the second burn, which was undoubtedly a sizeable fragment of ejected inhibitor material.

Analysis

The motor came up to operating condition rapidly, even more so than with the first BEM firings. The pyrogens and burst diaphragms were clearly effective in this regard.

Data was successfully collected for thrust, chamber pressure, and casing temperature. The thrust and pressure curves are shown in Figures 1 and 2. The design pressure, as determined by SRM.XLS, is shown for comparison. Clearly, the 1st phase firing experienced erosive burning with enhanced burn rate which produced a chamber pressure well in excess of the MEOP. The 2nd phase thrust and pressure curves exhibit behaviour closer to the design condition. However, it can be seen by the slow ramp up that delayed ignition was apparent. It is possible that some or all of the propellant segment end faces did not ignite immediately. Spikes can be seen in the 2nd phase pressure and thrust curves, near the end of the burn. These spikes coincide with “blackish” smoke that momentarily issued from the nozzle, as seen in the videos. As such, it is probable that the spikes were a result of inhibitor or insulation material being expelled through the nozzle.

Delivered specific impulse of both motor phases was an identical 133 seconds. This is the same value delivered by BEM firing #3. Total combined impulse was 2008 lb-sec (8931 N-sec) making this a 75% “M-class” motor. A summary of the motors performance is provided in Table 1 & Table 2.

To determine if “conventional” erosive burning was responsible for the 1st phase pressure/thrust profile, the erosive burning capability of SRM.XLS was modified to more realistically simulate erosive burning. The erosive burning that is modeled in SRM.XLS is based on the *multiplicative law*, whereby the standard *Saint Robert's* model for burn rate, **r**, is factored up to account for enhanced burning due to flow velocity through the grain core:

$$\mathbf{r} = a\, P_c^{\ n}\ [1 + k_v (G - G^*)]$$

where k_v is a constant, and G is the specific mass flow rate of the main flow, and G^* is a threshold flow rate. The term in brackets is the “erosive factor”.

The original version of SRM.XLS uses a simplification by applying the same erosive factor over the entire grain length. The modification that was subsequently made allows for an erosive factor that more realistically varies from *zero at the top segment* to a *maximum value at the lowest segment* (i.e. proportional to flow velocity). Trial values of G^* and k_v were then inputted to see if the resulting pressure curve would match the actual pressure curve for the 1st phase firing. The result of this analysis is shown in Figure 4. It can be seen that the simulated curve matches well to the actual curve. As such, it appears that conventional erosive burning was exhibited. The values used in the modified SRM.XLS were

Segment	G*	kv
#1 (top)	**20**	0.000
#2		0.015
#3		0.029
#4		0.044
#5		0.073
#6 (bottom)		**0.088** [1]

[1] Inputted value, other values of kv linearly interpolated.

Thermal data is shown in Figure 3. Maximum temperature on the casing outer surface was maintained below 150° C. (300° F) prior to 2nd phase firing. As soon as the 2nd phase began firing, the rise in casing temperature was extreme. This was immediately followed by an apparent fault in the thermal data acquisition, and the temperatures recorded following this event were clearly invalid. A similar fault occurred approximately 6 minutes later during motor cool down. The exact reason for the fault is currently unknown, however, it is speculated that attachment of the thermocouples directly to the conductive metallic casing could be to blame.

A post-firing teardown of the motor showed it to be in excellent and refurbishable condition

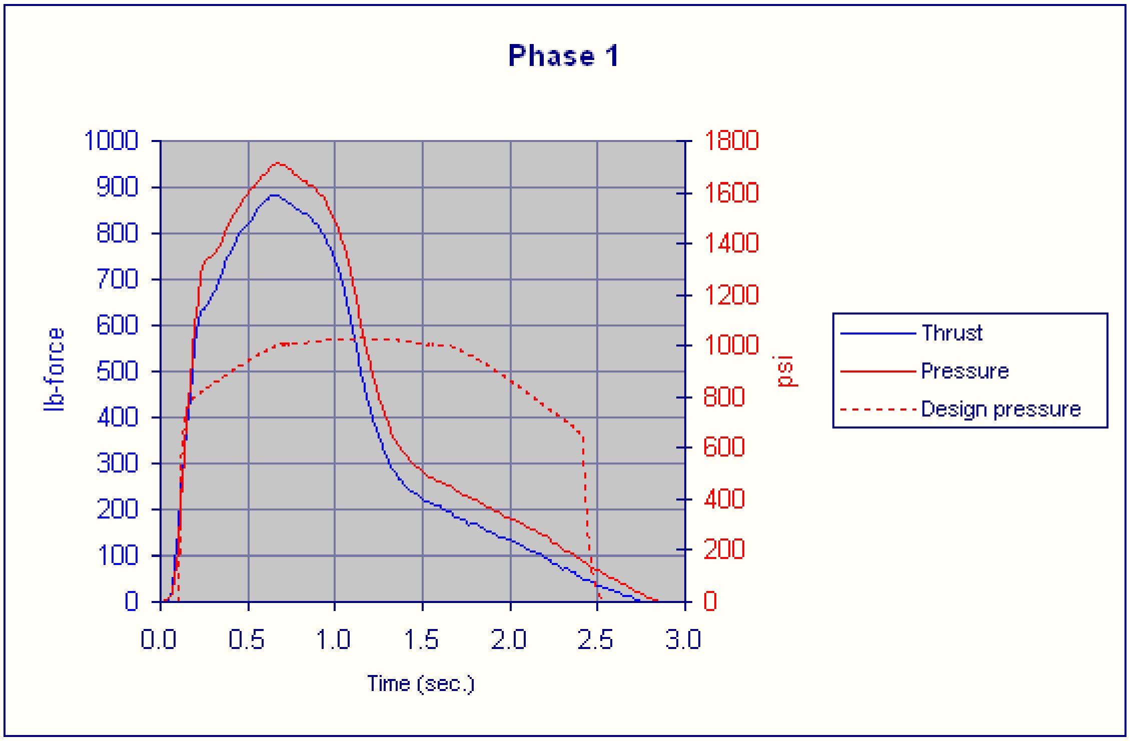

Figure 1a –1st phase thrust and chamber pressure data (English units)

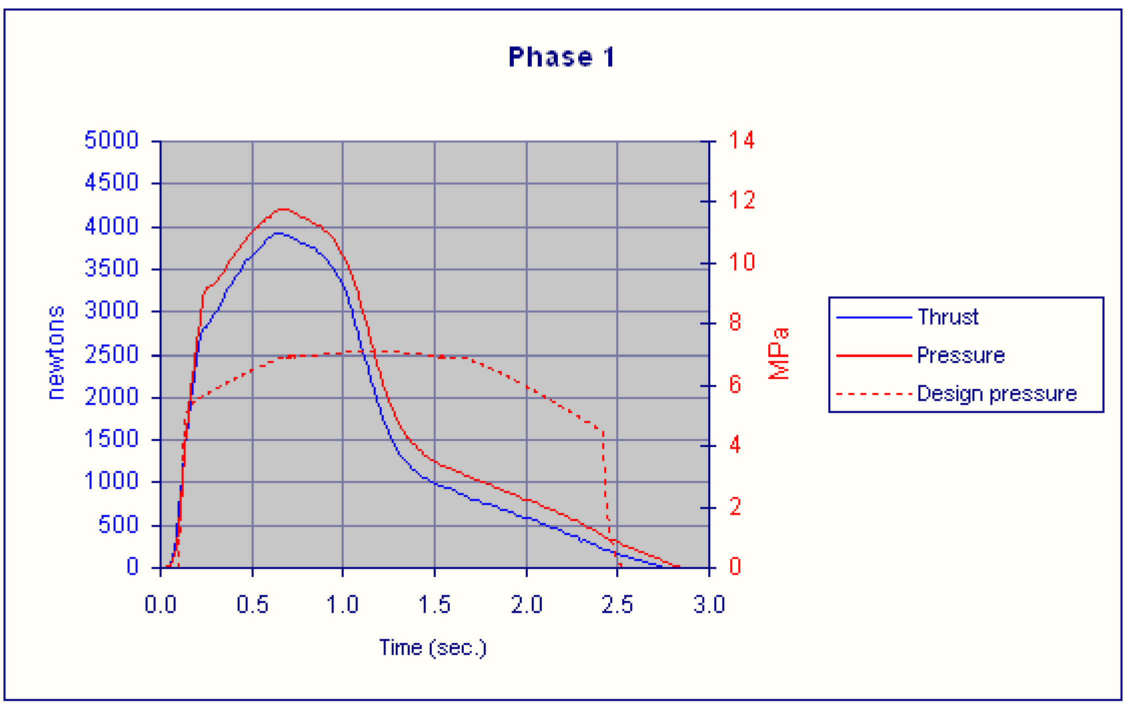

Figure 1b –1st phase thrust and chamber pressure data (SI units)

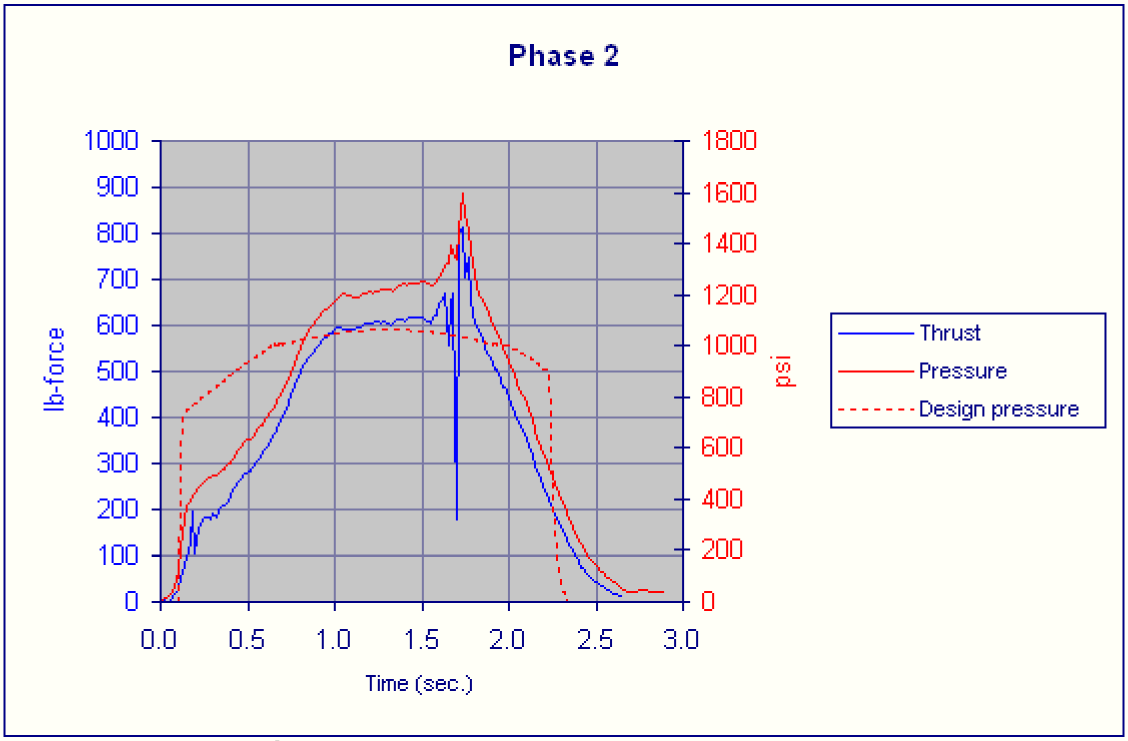

Figure 2a – 2nd phase thrust and chamber pressure data (English units)

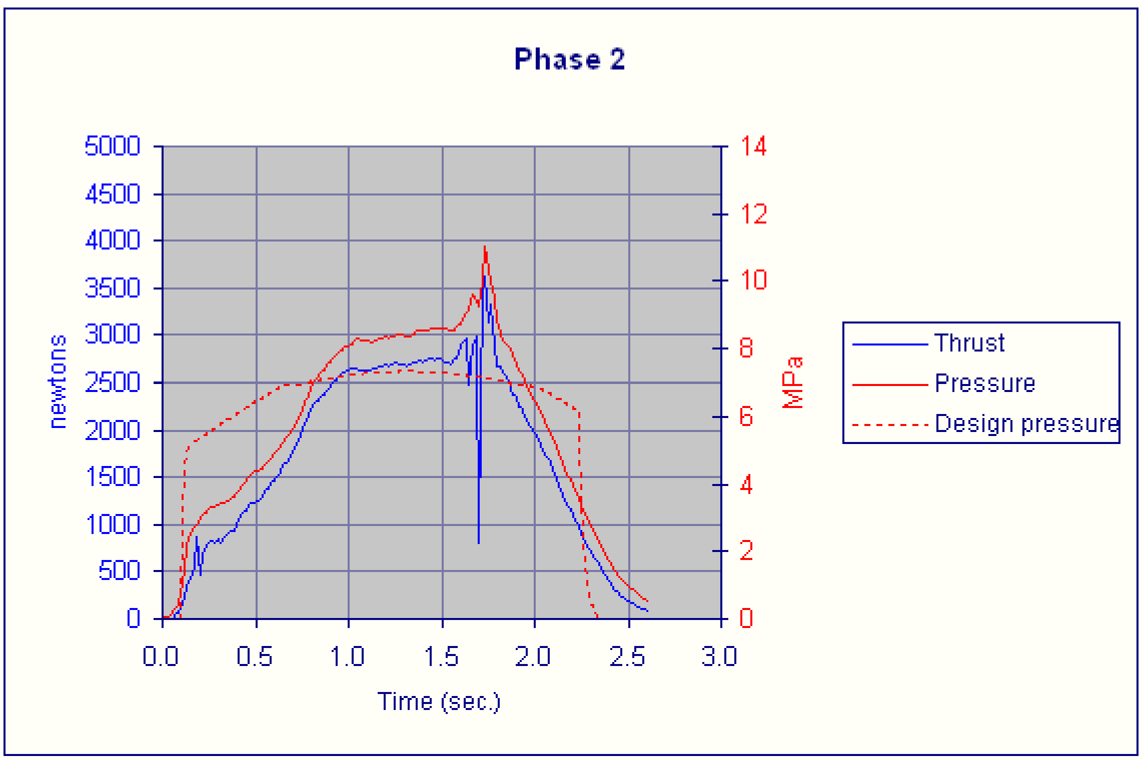

Figure 2b –2nd phase thrust and chamber pressure data (SI units)

Summary of 1st Phase Data & Performance					
Parameter	*Symbol*				
Throat diameter	D_t	**0.6410**	inches	**16.28**	mm
Propellant mass	M_p	**7.582**	lbs	**3.439**	kg.
Max. Thrust	F_{max}	**882**	lb-force	**3923**	Newton
Max. Pressure	P_{max}	**1710**	psi	**11.79**	Mpa
Avg. Thrust coefficient	$C_{f\ max}$	**1.52**	-	**1.52**	-
Total impulse	I_t	**1013**	lbf-sec	**4506**	N-sec
Specific Impulse	I_{sp}	**133.6**	lbf-sec/lbm	**133.6**	sec
c-star	c^*	**2878**	feet/sec.	**877**	metres/sec.
Ideal c-star	c^*_i	**2982**	feet/sec.	**909**	metres/sec.
c-star ratio	c^*/c^*_i	**0.97**		**0.97**	

Table 1 –Motor 1st phase performance values

Summary of 2nd Phase Data & Performance					
Parameter	*Symbol*				
Throat diameter	D_t	**0.6410**	inches	**16.28**	mm
Propellant mass	M_p	**7.456**	lbs	**3.382**	kg.
Max. Thrust	F_{max}	**813**	lb-force	**3616**	Newton
Max. Pressure	P_{max}	**1596**	psi	**11.00**	Mpa
Avg. Thrust coefficient	$C_{f\ max}$	**1.54**	-	**1.54**	-
Total impulse	I_t	**995**	lbf-sec	**4425**	N-sec
Specific Impulse	I_{sp}	**133.4**	lbf-sec/lbm	**133.4**	sec
c-star	c^*	**2931**	feet/sec.	**893**	metres/sec.
Ideal c-star	c^*_i	**2982**	feet/sec.	**909**	metres/sec.
c-star ratio	c^*/c^*_i	**0.98**		**0.98**	

Table 2 –Motor 2nd phase performance values

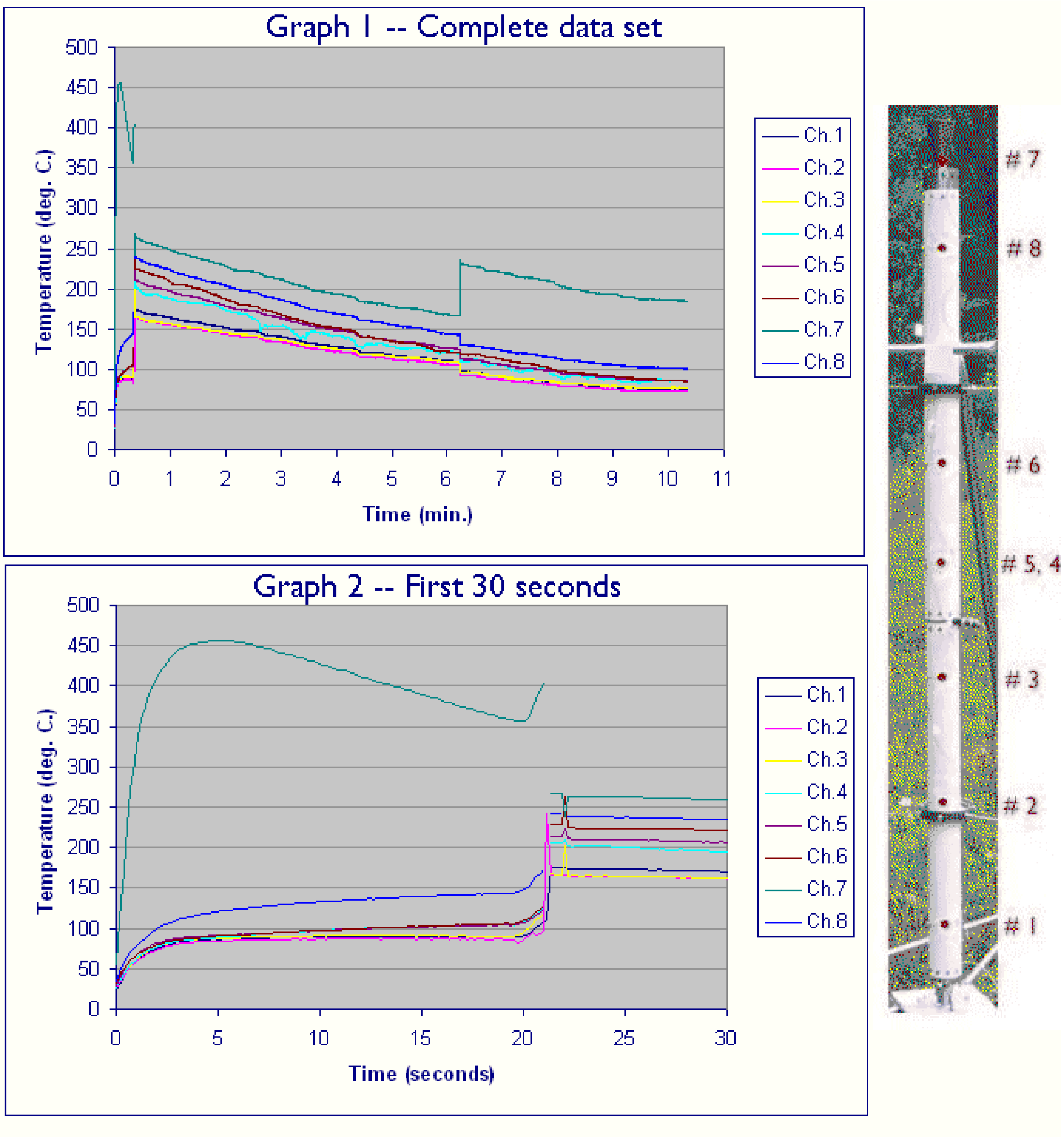

Figure 3 – Thermal data. Note: Sensors #4 & #5 were mounted on opposite sides of the motor and sensor #7 on nozzle throat

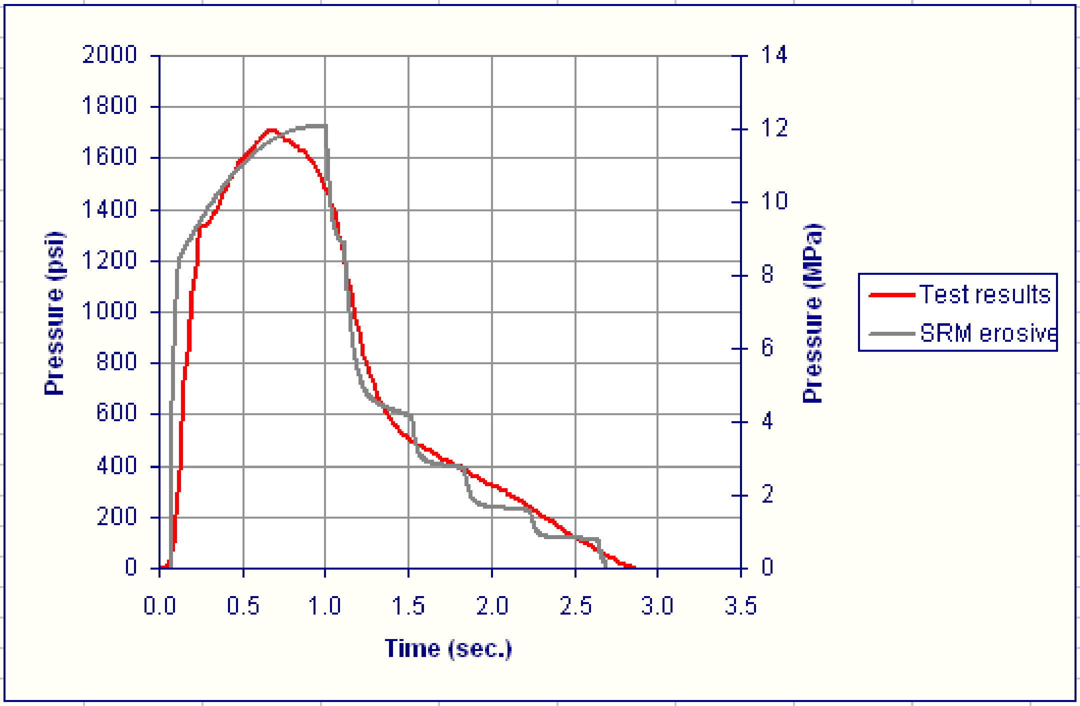

Figure 4 – Comparison of actual 1st phase pressure curve to SRM.XLS simulation with erosive burning

Conclusions

The main objective of the fourth BEM firing -- to prove the “dual-phase” concept -- was successfully achieved. The dual-phase “restartable solid rocket motor” concept was demonstrated to be feasible.

The motor behaved basically as expected, although the behaviour of both phases differed appreciably from the design condition. Erosive burning was shown to be a likely cause of the 1st phase deviation from expected behaviour. Erosive burning can be reduced or eliminated by utilizing a larger grain core. The core size is a tradeoff between the volumetric loading and tendency toward erosive burning.

The 2nd phase likely suffered from delayed ignition, a consequence of utilizing sorbitol-based propellant which is known to experience difficulties with prompt ignition. This concern will need to be investigated further. One possible cause may be inadequate segment spacing.

Delivered total impulse and specific impulse were close to that expected.

Both of the pyrogen devices functioned well in bringing the motor up to pressure rapidly.

The delay plug once again functioned as intended and successfully isolated the 1st and 2nd phase chambers during the 1st phase burn, and was successfully consumed prior to 2nd phase firing. This was true for all four BEM firings.

The data acquisition system for the load cells and pressure transducers worked very well. Good thrust and chamber pressure data was obtained. The temperature sensor system for the motor casings did not perform up to expectations. An unknown fault, possibly a result of grounding the thermocouples on the casing, resulted in faulty daata being collected. One lesson learned, as a result of this failure, was that adequate testing of new systems should be conducted under conditions that more closely simulate the expected operating environment.

Photos

Photo 1 – Grain segment casting mould used for 1st phase

Photo 2 – Propellant grain segments prior to coating ends with ignition primer

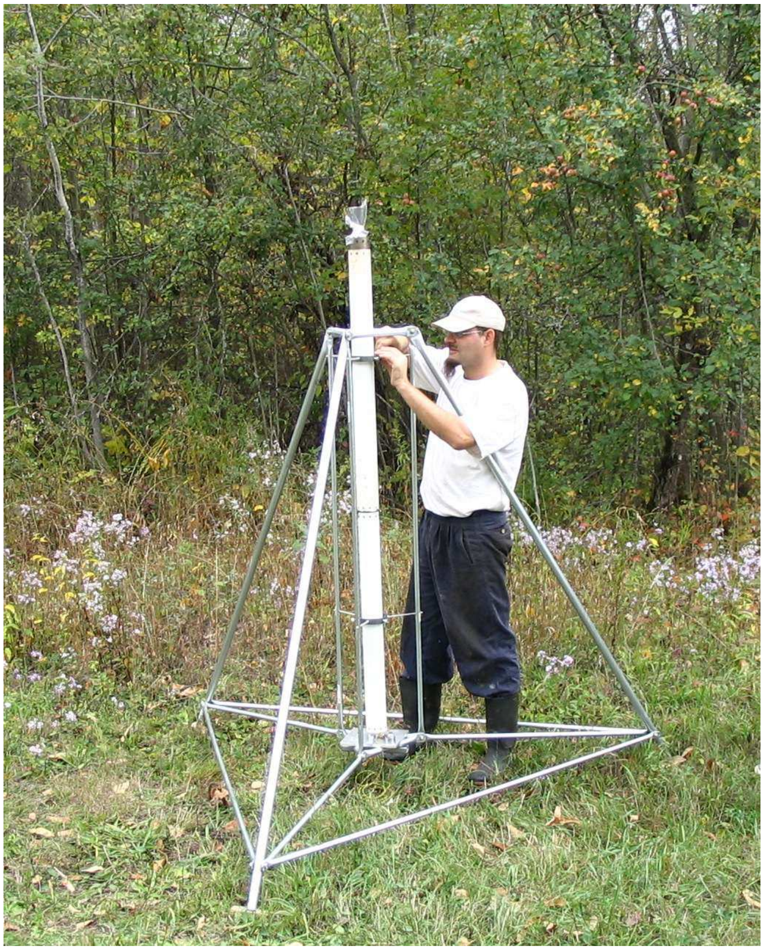

Photo 3 – Mounting BEM in static test stand

Photo 4 – Tarun configuring laptops used for data acquisition

Photo 5 – Daniel mounting thermocouples on motor

Photo 6 – Motor under full 1st phase thrust

Photo 7 – Following burnout of 1st phase, smoke issues from burning delay plug

Photo 8 – Motor under full 2nd phase thrust

Photo 9 – Close-up view of motor during 2nd phase operation

Photo 10 – Motor smoulders following burnout

Photo 11 –Tarun Tuli, Richard Nakka, Daniel Faber & Richard Graf saluting a successful test firing

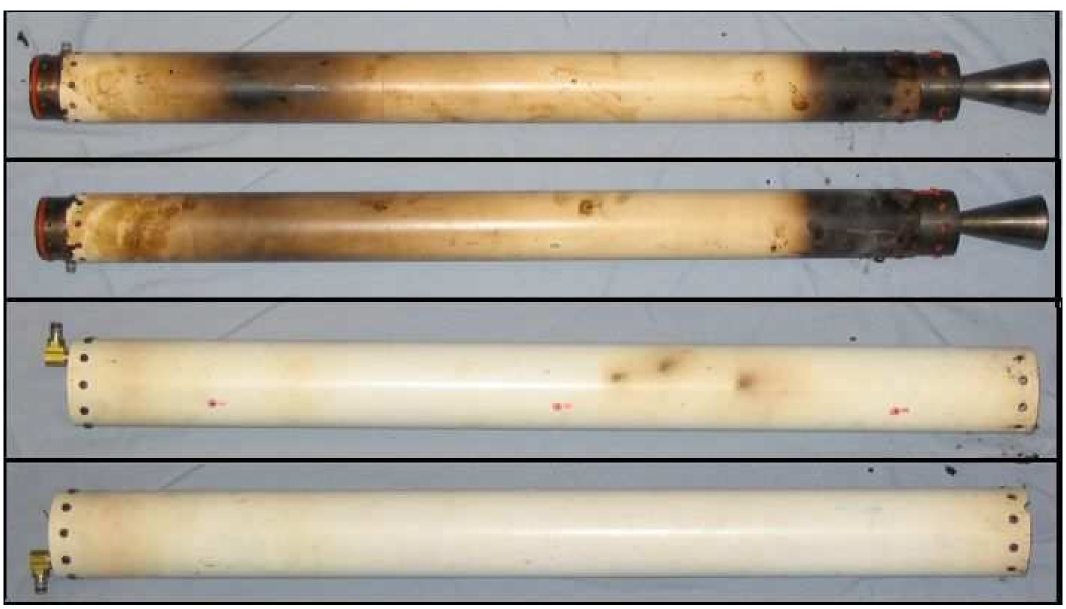

Photo 12 – Four views showing heat effects of both motor casings