



“1/4 Scale” Ballistic Evaluation Motor (BEM)

1st Static firing report

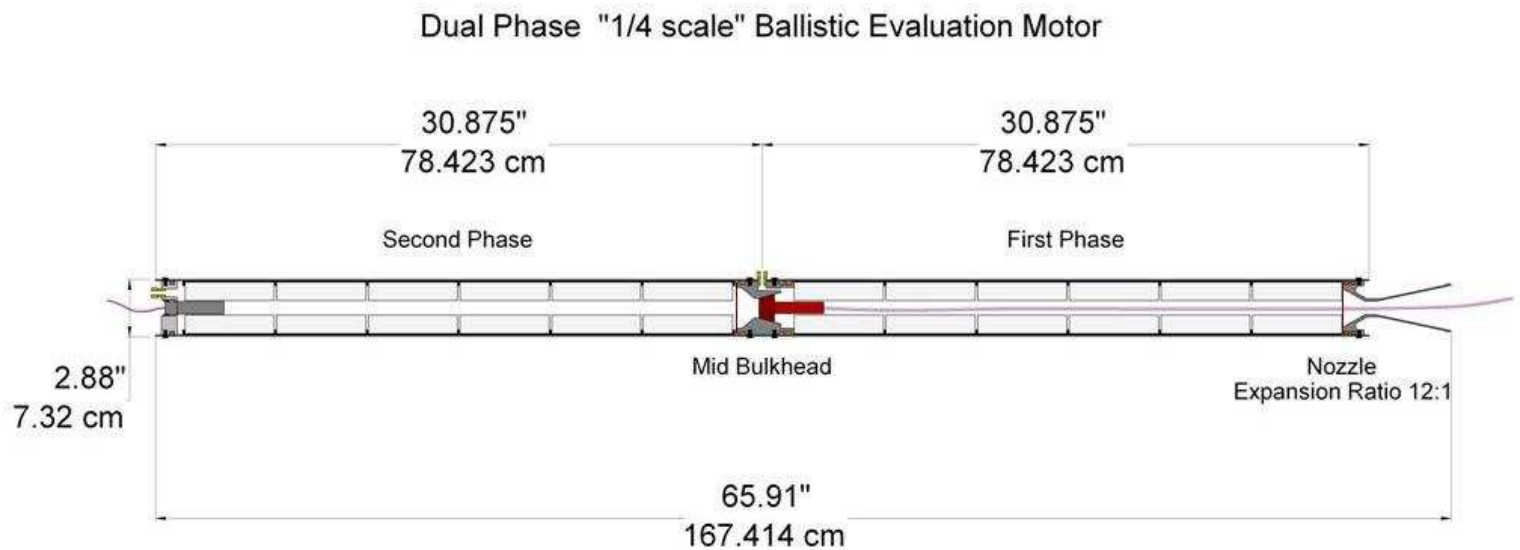
Rev. 2006/04/03

Introduction

This paper presents the test report detailing the first static firing of the “¼ scale” Ballistic Evaluation Motor (BEM). Note that ¼ scale refers to 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 construction details may differ significantly, especially with regard to materials used in the construction of the motor. The intent of 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.

Motor details

Details on the design and construction of the BEM are outlined in the Technical Specifications Paper Rev. 2005/08/28. Detailed dimensions can be found in the BEM CAD files of the motor. Overall dimensions and layout are summarized below.



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The BEM is designed to burn in two distinct phases, separated by a delay of approximately 15 seconds. Both phases are designed to be as similar as possible. Both phases incorporate head end pyrogen ignition and a burst diaphragm. The burst diaphragms, which were fabricated from nylon fabric reinforced epoxy, are designed to burst at 150 psi, without fragmentation. The motor is constructed almost entirely of steel. Steel tubing in the form of EMT tubing was chosen as the casing material because it has long been used successfully by AER enthusiasts as a reliable casing material for sugar-based propellants.

The nozzle is a conical profiled, deLaval supersonic type machined from steel (12L14), featuring 30° convergent and 12° divergent half-angles. The expansion ratio is 12:1, with MEOP being 1100 psi (7.6 MPa.). The nozzle is attached with alloy steel machine screws. To provide an effective and redundant pressure seal, two silicone o-rings are used in conjunction with silicone grease.

The mid-bulkhead, is designed to connect the two casing sections and to fully isolate the 1st phase chamber from the 2nd phase chamber during the operation of the 1st phase. An integral “delay plug” is ignited at the same time as the 1st phase and is sized to burn completely through within 15 seconds of ignition. The delay plug material is RNX propellant, comprised of a mixture of epoxy, potassium nitrate and iron oxide. The mid-bulkhead is machined from steel and is attached to each casing section with alloy steel machine screws. Two silicone o-rings are used on the 1st phase side, and one o-ring is used on 2nd phase side. All o-rings are used in conjunction with silicone grease. The burst diaphragm for the 2nd phase serves double duty as it also provides protection against accidental ignition of the 2nd phase grain from combustion heat of the delay plug. The mid-bulkhead also contains a pressure port to allow for measurement of chamber pressure during the first phase burn. Ignition of the 1st phase is accomplished with a small KN/dextrose/iron oxide propellant grain “pyrogen” with the same overall dimensions as the one contained within the pyrogen canister of the 2nd phase. The pyrogen grain for the 1st phase is not contained within a canister and is glued directly to the RNX plug. Additionally, the 1st phase ignition grain has sixteen small holes drilled into it to increase its initial surface area and to allow for flame impingement on the motor grain core surface. The design of the mid-bulkhead assembly is shown in Figure 1.

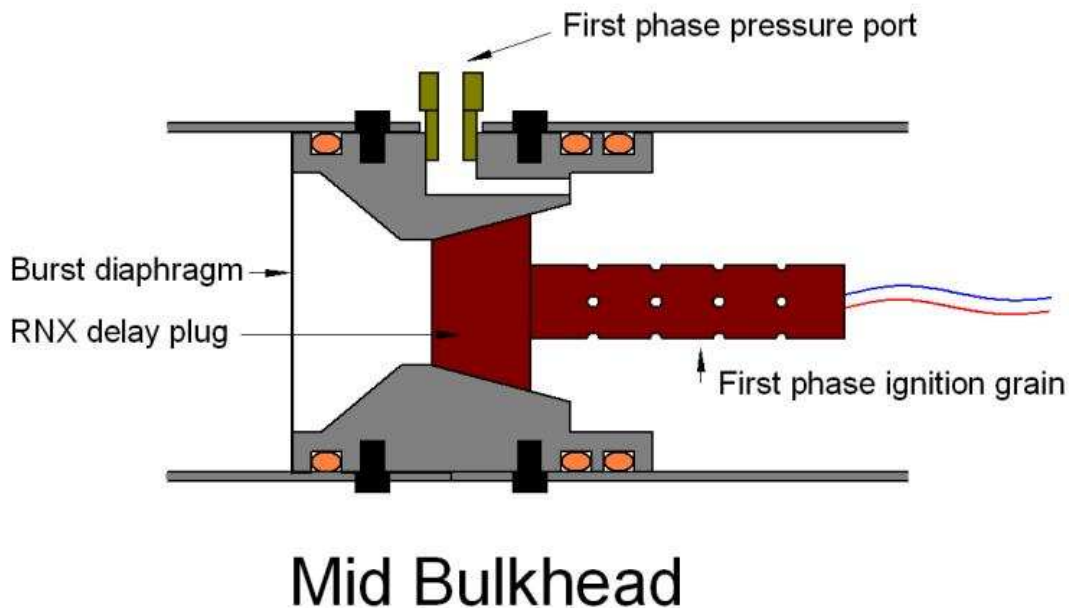


Figure 1 – Design details of mid-bulkhead assembly

The upper bulkhead is machined from 6061-T6 aluminum alloy. It is attached with alloy steel machine screws. For sealing, the bulkhead is provisioned with a single o-ring used in conjunction with silicone grease. Additionally, silicone grease was applied to all surfaces exposed to heating. The bulkhead contains a pressure port for measurement of 2nd phase chamber pressure. This bulkhead also has a provision to retain the pyrogen igniter canister.

The Pyrogen Igniter as installed in the forward bulkhead is illustrated in Figure 2. The canister is machined from stainless steel bar stock, and retained by a retaining ring (snap-ring). The igniter leads are fed through the two holes on the top of the canister, and are sealed and secured by filling the holes with epoxy.

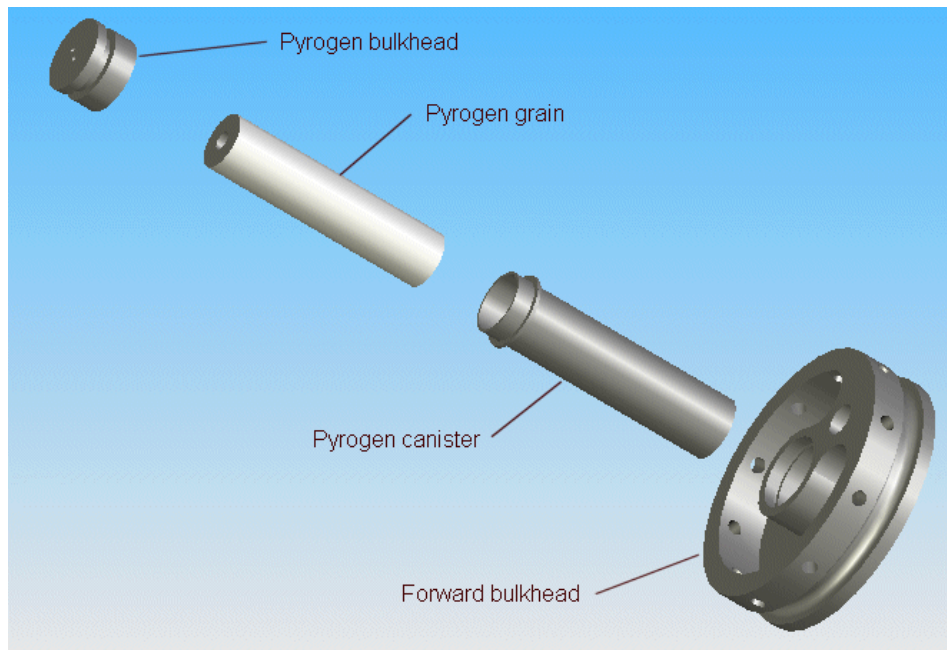


Figure 2 – Design details of forward bulkhead assembly

The casing material for this first test was *Republic* brand Electric Metallic Tubing (EMT). The casing was hydrostatically tested and on the initial test was found to leak at the mid-bulkhead. A quick look at the casing showed that the welded seam in the area of the leak contained a “valley” that allowed pressure to get past the o-rings. This area was filled with JB-weld and sanded smooth and later proved to provide a good seal. The EMT’s zinc coating was left intact.

Propellant Grain

The propellant grain consists of a total of 12 segments, six for each phase. Segments were separated by 0.10” (2.5 mm) thick spacers made of ABS plastic. Spacers were also placed between the nozzle, mid-bulkhead, forward bulkhead, and the corresponding adjacent propellant segment. This firing was conducted with KNSB propellant cast in the

“standard” heat cast method in a standard Oxidizer/Fuel ratio of 65/35. A cast iron pot placed on a thermostatically regulated electric skillet was used to heat the propellant. Propellant was heated to a temperature of 275° F. (135° C.). The propellant was prepared two segments at a time. The KN was milled potassium nitrate from *Firefox* and was used as received. The Sorbitol was *Now Foods* brand from *HerbsMD* and was also used as received. The weighed ingredients were then mixed together into a large *Tupperware* container. This container was shaken by hand for approximately one minute then poured through a flour sifter into another *Tupperware* container. This process was repeated several times. Propellant segments were cast into paper casting tubes with an ID of 2.6” (66mm). Hi-temperature grease was applied to the ID of the casting tubes to allow them to be easily removed after the propellant was fully cured. Once the segments were fully cured and had the casting tubes peeled off they were cleaned with acetone to remove any grease. Segments then had the inhibitor applied. Inhibitor layer consisted of 4 wraps of fiberglass cloth and polyester resin. Application was found to be quite simple, clean and effective. Application was done two layers at a time, with one strip of glass being long enough for two layers. The resin was brushed onto a segment and then rolled over a length of fiberglass that was laid out on a piece of wax paper. Application of the inhibitor was done in two steps mainly because it was found that the brushed-on layer of resin was able to wet out two layers of cloth. The actual size, weight, and densities are shown below. Although of somewhat lower density than hoped for, it was encouraging that they were very consistent.

Both ends of each segment were coated with potassium nitrate/charcoal primer.

Phase one grain

Total weight 7.963 lbs (3.612 kg)
Average segment length 4.34” (110 mm)
Average OD 2.61” (66.3 mm)
Average core diameter 0.74” (18.8 mm)
Density ratio .936

Phase two grain

Total weight 8.018 lbs (3.637 kg)
Average segment length 4.40” (112 mm)
Average OD 2.61” (66.3 mm)
Average core diameter 0.74” (18.8 mm)
Density ratio .929

Ambient burn rate of the batch was measured to be 0.245 cm/sec., which is typical.

Test Firing Report

by Randy Dormans

The firing was conducted on Saturday January 21, 2006. It was a cool morning, but the sky was clear and once Peter and I got busy setting things up it was pretty comfortable. By the time we conducted the test it was in the mid 60’s. Peter assembled that test equipment, while I prepared the motor. The assembly of the motor took quite a bit longer than I expected. Just putting in the 40 screws took a bit of time. Assembly of the 1st phase was a bit tricky in that I had the mid-bulkhead fully assembled as in Figure 1, and had to feed the igniter wire through the casing towards the nozzle end and feed the wire through a segment core and then slide that segment into the casing. I didn’t have the mid-

bulkhead in the casing though because I was afraid that a segment could slide down the casing and maybe bump the pyrogen grain and dislodge it from the delay plug. Once I got the six segments in, I installed the mid-bulkhead and then the nozzle. The assembly of the second phase was a bit quicker.

Once we had the motor loaded into the test stand it took a bit of time to connect the temperature sensors and hook-up the plumbing to the pressure ports.

The two separate igniters had extensions attached to them that ran back to our shelter. The ignition box was attached to the first phase igniter and after Peter's countdown I pushed the button and the motor roared to life. I kept my eyes on the motor looking for black smoke to indicate that the delay plug was burning. Meanwhile, Peter was next to me switching the leads from the igniter box to the other igniter and counting down the time left before I fired the second phase. When he got to 15 seconds, he called for me to fire the second phase. I hesitated partly because I still saw black smoke coming out of the nozzle and thought that maybe the delay plug had not burned completely through and partly because I was amazed at how brightly the nozzle had been glowing during the burn and also by the size of the flame that came out of the nozzle after the burn was complete. Both were things that I had never seen before from a sugar motor. At the time, it seemed like a fraction of a second, but the video shows it to be about four seconds. So four seconds after the call I ignited the second phase and the motor roared to life once again. As the motor came to full pressure it sputtered two or three times ejecting some leftover fiberglass inhibitor from the expended 1st phase. About 2/3 of the way through the expected burn time there was a dull popping sound and the motor and stand slammed into the ground in a cloud of smoke.

Analysis

Examination of the motor following the firing showed that the 1st phase casing had burst open at the welded seam just aft of the mid-bulkhead. Despite tearing loose from the stand, good pressure and thrust data was obtained from both the 1st phase and 2nd phase firings, as shown in Figure 3. Data from the thermal sensors, which had been attached to the motor casings, was not salvaged.

With regard to what led to the casing failure, the initial thought was that a nozzle blockage had occurred, leading to a pressure spike which caused the failure. However, examination of the collected pressure and thrust data showed that there was no pressure spike at the moment of failure. Rather, the chamber pressure had at this point started to tail off to some extent, as can be seen in the 2nd phase pressure curves in Figure 3 (cyan & green curves). Subsequent examination of the damaged casing showed that the butt-welded seam was of inferior quality to that usually found on EMT tubing. In hindsight, this deficiency had been hinted upon during the proof pressure hydro-test when leakage occurred. Examination of new sections of *Republic* brand tubing revealed that this was indeed the case. The weld was not the full thickness of the tubing wall. This is unlike the seam of *Allied* brand tubing (the usual brand of EMT used for motor casings), which has consistently proven to be of excellent quality. Thermal loading with consequential reduction in seam strength were contributing factors that led to the failure.

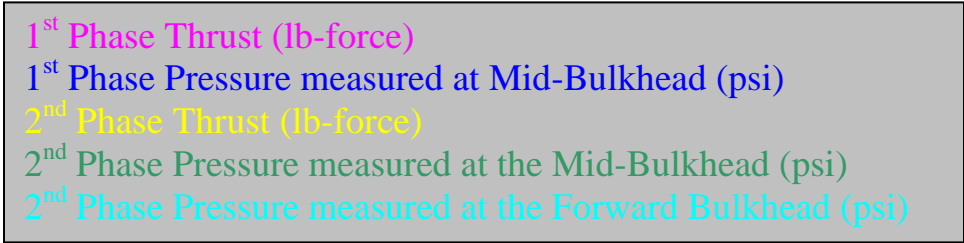
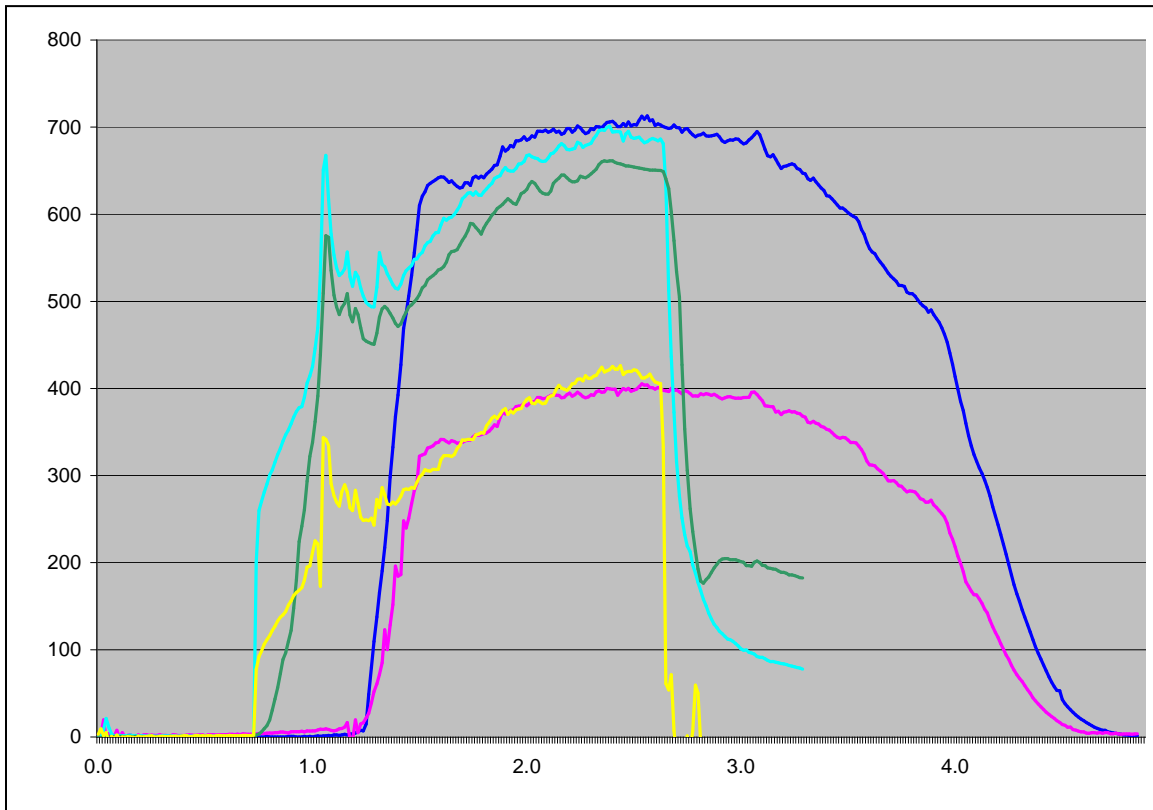


Figure 3 – Measured thrust & pressure data

As is seen in the pressure and thrust curves of Figure 3, the motor came up to operating state quickly, for both phases of operation. The pyrogens were clearly effective in this regard. The spikes at the beginning of the 2nd phase burn were the result of inhibitor debris being ejected through the nozzle, as was witnessed by the observers. The shapes of the 1st phase curves were fairly close to the shape of the design curve. The performance curves did not exhibit the unwelcome “triangular” shape that is often seen in KNSB powered motors.

Using the curves shown in Figure 3, the motor performance was calculated for 1st phase operation and is given in Table 1. Figure 4 illustrates the Thrust Coefficient (C_f), computed from chamber pressure, thrust, and nozzle throat area.

Summary of 1st Phase Data & Performance					
Parameter	Symbol				
Throat diameter	D_t	0.6635	inches	16.85	mm
Propellant mass	M_p	7.963	lbs	3.612	kg.
Max. Thrust	F_{max}	405	lb-force	1802	Newton
Max. Pressure	P_{max}	713	psi	4.92	Mpa
Max. Thrust coefficient	$C_{f\ max}$	1.66	-	1.66	-
Total impulse	I_t	989	lbf-sec	4398	N-sec
Specific Impulse	I_{sp}	124	lbf-sec/lbm	124	sec
c-star	c^*	2508	feet/sec.	765	metres/sec.
Ideal c-star	c^*_{i}	2982	feet/sec.	909	metres/sec.
c-star ratio	c^*/c^*_{i}	0.84		0.84	

Table 1 – Measured test values

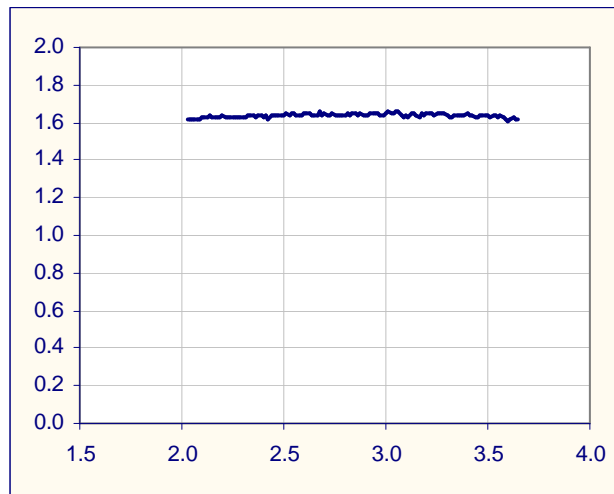


Figure 4 -- 1st phase Thrust Coefficient over steady-state duration of motor operation based on measured data

Upon inspection, these performance values indicate a markedly lower performance than expected, with the exception of Thrust Coefficient, which is plotted in Figure 4. The Thrust Coefficient, which was nicely constant over the steady-state operating duration, was significantly higher than expected. Investigation of why this was the case led to the conclusion that calibration of both the load cell and the pressure transducer was imprecise. Inconsistencies turned up during attempts to recalibrate the sensors following the discovery of less-than-expected performance.

As an “academic exercise” to attempt to resolve the issue, and to extract useful tentative motor performance from this first firing, the chamber pressure data was adjusted to obtain a Characteristic Velocity (“c-star”) value that is typical of KNSB and other “sugar” propellants. C-star is a thermochemical property of a given propellant and tends to be consistent, regardless of motor particulars. Experience has shown that combustion of sugar propellant tends to be quite efficient and typically produces 95%, plus or minus a few percent, of the ideal (theoretical) c-star value. The value of c-star based on the

measured data, as shown in Table 1, was 84% of ideal, clearly unrealistic. The adjusted pressure plot based on a c-star ratio of 95% is shown in Figure 5, in comparison with the design curve.

Another indicator of miscalibrated pressure data is the unusually high value for the Thrust Coefficient (Figure 4). As shown in Table 1, the maximum value for the computed Thrust Coefficient based on measured data was $C_f=1.66$. Experience based on numerous static firings of sugar-based motors suggests a more realistic value of approximately $C_f=1.5$. Using the adjusted pressure values based on a 95% c-star ratio, the revised maximum Thrust Coefficient becomes $C_f=1.47$, as realistic value.

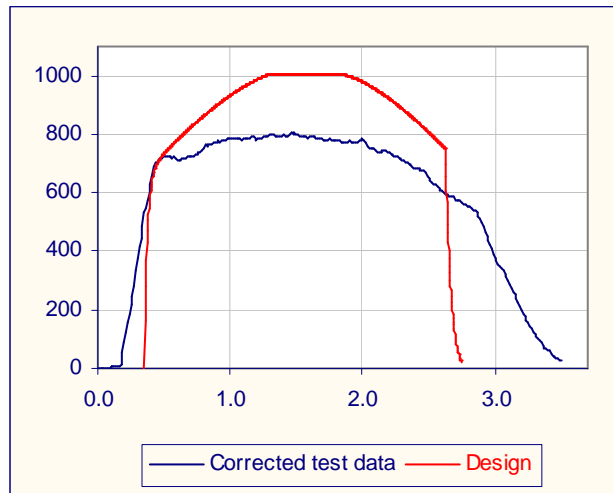


Figure 5 – Chamber pressure comparison

The chamber pressure is nevertheless significantly lower than design, and the burn time is longer. This is not entirely unexpected, as the design curve is based on propellant made from finely milled KN and made from extremely well blended KN and sorbitol, neither of which represented the actual propellant used in this first test firing. Consequently, the propellant burn rate was slower, leading to lower chamber pressure and a longer burn time. The presence of residual moisture in the propellant is another possibility that, if present, would be a contributing factor to the slower burn rate.

With regard to the post-firing condition of the motor, damage was relatively light. Other than the burst casing, the only other significant damage was a bent nozzle due to impact with the ground.. The throat was measured and no measurable erosion was found, despite the extreme heating.

Conclusions

The main objective of this first firing of the BEM, to prove the “dual-phase” concept, was largely achieved. The mid-bulkhead with integral delay plug performed as expected and successfully isolated the two combustion chambers. The delay grain was consumed following 1st phase firing, although at a somewhat slower rate than expected. The 2nd phase fired well and the presence of the mid-bulkhead did not seem to be detrimental to the performance. In fact, the 2nd phase maximum thrust was slightly higher than that of the 1st phase. The shape and magnitude of both thrust curves were similar, and basically followed the profile of the design curve. Tentative performance numbers were obtained. The 1st phase casing failure appeared to be due more to “misfortune” than anything else. Data collection worked well with the exception of that of the thermal sensors. Precise calibration of the pressure and thrust sensors proved to be more of a challenge than expected.

Clearly, the first BEM firing was a learning experience and a number of changes will be implemented for the second BEM firing:

- *Allied* EMT tubing will be used for both casings
- A higher hydro-test pressure will be used
- A means of insulating or cooling the 1st phase casing at the critical location will be implemented
- Pressure sensors and load cells will be redundant and more carefully calibrated
- Thermal sensors will be improved in terms of mounting, calibration and data acquisition
- Propellant will be prepared more similarly to that of the design condition.
- The replacement nozzle will have a heavier throat section

Photos



Photo 1 – Propellant grain segments prior to inhibiting



Photo 2 – Nozzle (left) and installed mid-bulkhead (right)



Photo 3 – Instrumented $\frac{1}{4}$ Scale BEM in static test stand



Photo 4 – 1st phase motor undergoing full thrust



Photo 5 – Nozzle glowing after 1st phase burnout. Smoke from burning delay plug



Photo 6 – Ruptured 1st phase casing aft of mid-bulkhead