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SOLID FUEL RAMJET (SFRJ) PROPULSION FOR ARTILLERY PROJECTILE APPLICATIONS – CONCEPT DEVELOPMENT OVERVIEW

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The concept of using solid fuel ramjet (SFRJ) propulsion to increase the range of artillery projectiles is being investigated at Somchem. Initial work was carried out on a 76 mm smooth bore kinetic energy penetrator. The focus has shifted to a l55 mm gyroscopically stabilized projectile. The initial objectives set to the team were a) To comply with the NATO Joint Ballistic Memorandum of Understanding, JBMoU, b) Range of at least 70 km, c) Payload of 5 kg HE or 40 dual-purpose submunitions and d) Market price of less than 5000 US$ excluding the course correction fuse.
The project was divided in three subsystems for the concept phase, namely a) Structural Design, b) Propulsion and c) Aerodynamics. The experimental design, execution and results of the wind tunnel tests are discussod in a separate paper by Stockenström and Dionizio [2].
Initial firings were carried out with special charges made up to obtain a muzzle velocity of 900 m/s.

MECHANICAL / STRUCTURAL DESIGN

Drive Plug

The drive plug blocks off the rear end of an otherwise hollow projectile and in the initial layout, it also carries the driving band and therefore has to transfer spin-up torque to the rest of the projectile.

A contrasting and challenging requirement of the drive plug is that it initially has to be fixed to the projectile, but also has to separate from it as soon as possible after muzzle exit. Clean and reliable separation with minimum disturbing forces being transferred to the projectile was achieved (Fig. 1). One way to help expel the drive plug is to employ conical contact surfaces but with a large enough included angle (larger than the self-locking angle or angle of friction).

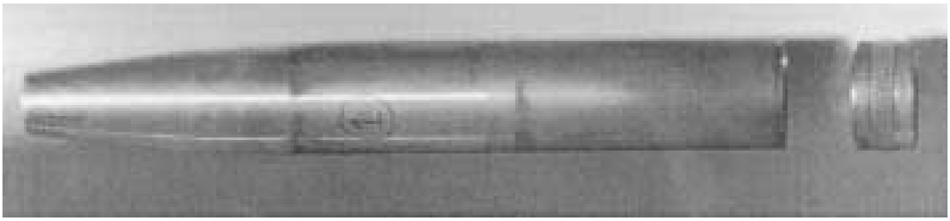


Figure 1. Clean separation of drive plug just after muzzle exit.

The interface between the drive plug and the projectile has to be strong enough to resist environmental testing, normal handling, as well as ramming forces. A typically higher value of ram retardation was measured as 700 g's.

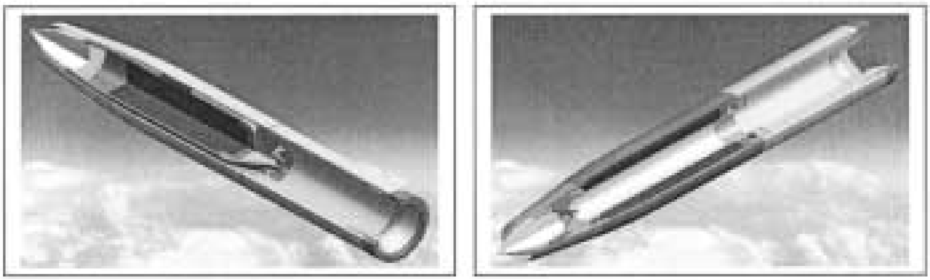
Two different drive plug interfaces were evaluated through actual test firings of projectiles with a representative mass and roll inertia. Axial acceleration forces are used to break initial binding/bridging geometry between the drive plug and the ring carrying the nozzle. One concept tested, relied on friction at a short conical surface, as well as a normal contact surface, to transfer torque. The other type of interface relied on positive interlocking to transfer torque and fulfilled all requirements except that it is considered relatively expensive to manufacture.

Driving Band

Locating the driving band on the projectile itself, and not on the drive plug, is another option being evaluated. This largely eliminates torque transfer problems but increases aerodynamic drag on the projectile. Another consequence of a forward driving band is the requirement for some kind of sealing at the interface between the projectile and the drive plug.

General Structural Design and Layout

Although the drive plug involves a domed shape, it is still one of the heavier components. Finite element structural analysis was used to minimise the drive plug mass. Both the drive plug and propellant casing are made of a high strength and toughness cold work tool steel (offering low distortion during vacuum heat treatment). An alternative material like maraging steel could also be considered but might only be economical at production quantities. The casing is subjected to enormous axial acceleration forces (130 000 m/s^2). However, every effort has to be made to ensure that components to the rear of the projectile are as light as possible to ensure a forward centre of gravity as required for stability. A study was undertaken in parallel to investigate the viability of making the propellant casing from composite material.



a) b)

Figure 2. Layout with a) central payload b) annular payload.

A concept still to be further investigated involves a projectile with no drive plug at the rear, but rather a plug against chamber pressure located inside and at the front of the propellant casing. This allows one to design a lighter casing due to pressure equalisation together with a forward placed driving band. Disadvantages of this design, compared to the concept described above, are increased drag due to the integral driving band, and difficulties in ensuring clean expulsion of the inner plug through the nozzle.

Two general projectile layouts were considered: a central payload (Fig. 2) vs. an annular payload. A central payload requires one or two sets of radial webs to support it inside the forward body. It offers the best shape and space to accommodate available sub-munitions. Negative aspects include manufacturing cost and structural risks due to the webs carrying a relatively large mass, and also the complexity of expelling the sub-munitions. A benefit of the annular layout is that the major load paths are aligned through the outer walls of the projectile structure offering a more effective and robust structure. No thin walls would be in direct contact with the barrel because of the warhead inherent thickness. Other advantages of the annular layout are perceived lower cost and a better stability margin due to higher roll inertia.

The current demonstrator round also has a center body supported by webs, but it involves the much smaller and lighter inlet cone and diffuser. Forces on the webs includes axial acceleration, spin acceleration as well as lateral acceleration and vibration. The lateral forces considered include: a) centrifugal force due to barrel curvature (e.g. due to non-uniform temperature distribution), b) centrifugal force due to a slight non-eccentrical mass distribution in the spinning projectile, c) and lastly forces due to transverse recoil motion. Lateral accelerations were previously measured and yielded substantial values – typically in the order of 2000 g's.

Threaded Interfaces

Threaded interfaces are being used between the nozzle ring and the propellant casing, and between the propellant casing and the forward section. These interfaces required a major design effort due to the large spin acceleration (230 000 rad/s^2) plus accompanied torque involved. Initial failure was caused by excessive radial deformation as the thread

Home
Table of Contents

wedges itself open under torque loading. This was confirmed by non-linear *finite element* analysis, but there were aggravating factors. The friction coefficient used to calculate the axial force from the torque, proofed to be substantially lower in practice due to the dynamic conditions involved. Secondly, there was the amplification of structural response due to the dynamic loading conditions ("overshooting"). A further detrimental effect was the returning tensile stress wave originating from the drive plug impacting against the rear of the projectile, after fracture of the temporary interface that initially holds the drive plug (Fig. 3).

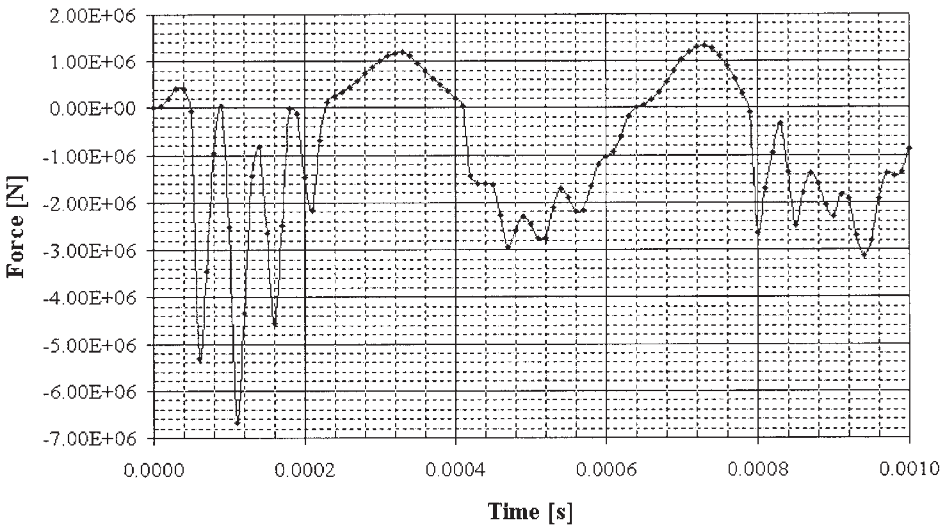


Figure 3. Axial force at mid joint due to impact from dynamic FE analysis.

Several possible solutions were considered to solve the threaded interface problem. First of all, sufficient joint length and a course thread pitch are required. Increasing the thickness of the relevant components has to be done with due care, because it impacts negatively on the total mass as well as center of gravity. Butting up against a bevelled shoulder could also help to counter thread dilation. A *Buttress* thread form is ultimately a better solution but more complicated (costly) to manufacture and inspect.

Propellant Grain

The structural integrity of the propellant grain was evaluated through test firings. The HTPB based propellant formulation was fiber reinforced, but also contained metal particles. The grain successfully survived the severe launch accelerations.

PROPULSION

Combustion tests were conducted at the Somchem Hot Air Blow-Down Test Facility to determine the basic performance characteristics of a solid fuel ramjet (SFRJ) propulsion system representative of that to be used with a 155 mm artillery projectile configuration [1]. The tests are discussed briefly in the following paragraphs. The test set-up is shown in Fig. 4.

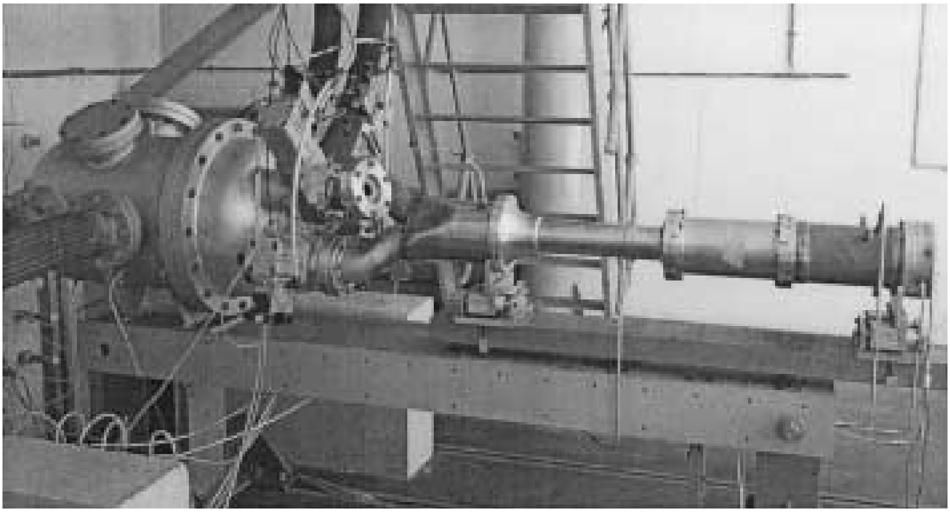


Figure 4. Test set-up.

The main objectives of the first phase exploratory tests were the following:

1) Demonstrate successful ignition.
2) Investigate the effect of operating conditions, mainly stagnation temperature (T_{t0}) and mass flow rate ($\dot{m}_a$) of incoming air, on combustor performance.
3) Acquire test data that could be used to improve the accuracy of propulsion system performance predictions.
4) Investigate the effect of mixing chamber length on combustor performance.

Experimental set-up and test hardware

Transition valves were used to dump vitiated air during facility start-up until the required operating conditions were achieved. At this point, the grain is ignited and the transition valves switched to redirect all by-pass air through the SFRJ combustor.

The modular SFRJ test hardware allowed convenient changes to the basic combustor configuration (i.e. port diameter, exit nozzle diameter and aft mixing chamber length). Basic dimensions and other relevant information of the test hardware are listed below:

Station 2 diameter *(d_2)*:	72 mm
Fuel port diameter *(d_p)*:	94.4 mm ≤ d_p ≤ 138 mm
Mixing chamber length *(l/d_4)*:	2 for tests PR_1 to PR_5, 0 for test PR_6
Station 4 diameter *(d_4)*:	138 mm
Exit nozzle area ratio *(A_5/A_4)*:	0.272
Total fuel mass *(m_f)*:	~2.25 kg

Test conditions and summary of results

Six tests were conducted and test conditions are summarised in Table 1. Also listed are average values calculated for fuel mass flow rate *($\dot{m}_f$)*, burn rate *(r_b)* and air/fuel ratio *(o/f)*. The remaining sliver mass at the end of a test is also listed. As mentioned previously, one of the main objectives of the test series was to determine m_f or r_b as a function of T_{t0}, $\dot{m}_a$ and d_p. Tests PR_1, PR_4 and PR_2 were therefore conducted at comparable T_{t0} while $\dot{m}_a$ was reduced from 5.24 kg/s to 1.37 kg/s. It was evident that the burn time (and therefore also r_b and $\dot{m}_f$) is strongly influenced by changes in $\dot{m}_a$.

Table 1. Test conditions with some measured/calculated parameters

		PR_1	PR_4	PR_2	PR_1	PR_5	PR_3	PR_5	PR_6
T_{t0}	K	705	691	676	**705**	**587**	**528**	587	584
$\dot{m}_a$	kg/s	**5.240**	**3.482**	**1.371**	5.240	5.277	5.246	5.277	5.335
$\dot{m}_f$	kg/s	0.083	0.069	0.044	0.083	0.076	0.071	0.076	0.079
o/f	-	62.9	50.6	30.8	62.9	69.3	73.8	69.3	67.5
r_b	mm/s	0.901	0.699	0.467	0.901	0.780	0.744	0.780	0.808
m_{sliver}	Kg	0.075	0.068	0.038	0.075	0.117	0.129	0.117	0.148

During tests PR_1 PR_5 and PR_3 the $\dot{m}_a$ was kept constant while T_{t0} was reduced from 705 K to 528 K. Test results indicated that r_b is less sensitive for variations in T_{t0} over the mentioned range.

Tests PR_5 and PR_6 were conducted at similar operating conditions, the only difference being the removal of the mixing chamber during test PR_6. This was done to evaluate the effect of the mixing chamber on combustor performance.

Approximate values of $\dot{m}_f = f(t)$, and therefore also averaged values of $r_b = f(t)$, were derived from the $p_2 = f(t)$ integral. Shown in Fig. 5 is the relationship between r_b, T_{t0} and $\dot{m}_a$ for a specific d_p.

Home
Table of Contents

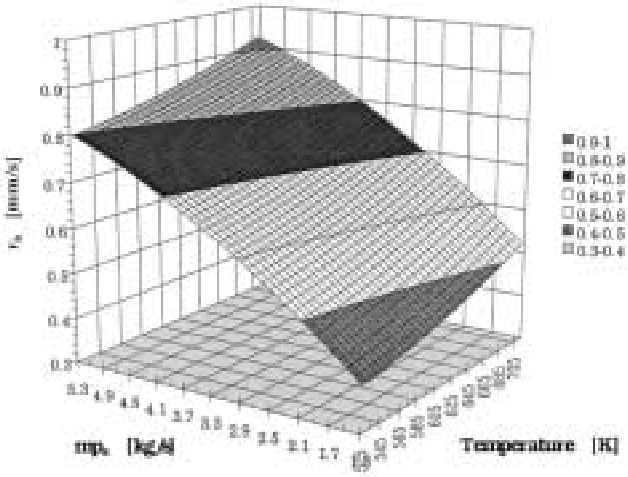


Figure 5. Fuel burn rate as a function of T_{t0} and $\dot{m}_a$ for a specific d_p.

Discussion

A brief summary of the test results is listed below:

1) Successful and reliable ignition was demonstrated.
2) Good and stable secondary combustion was demonstrated within the temperature range of 675 K $\leq T_{t0} \leq$ 705 K and mass flow range of 1.37 kg/s $\leq \dot{m}_a \leq$ 5.24 kg/s.
3) $\dot{m}_f$, and therefore also r_b and burn time, is strongly dependant on $\dot{m}_a$. The effect of T_{t0} on $\dot{m}_f$ is less pronounced.
4) Removal of the mixing chamber had a smaller than expected effect on combustion performance. Less stable combustion was noticed when the mixing chamber was removed.
5) Residual mass of fuel after the test (sliver mass) as percentage of initial fuel mass varied between 1.7 % and 6.5 %.

In general, the SFRJ combustor performed well with good combustion efficiency. First indications of combustion stability and flameout limits seem to be acceptable.

INLET

Development and optimization of the axi-symmetrical inlet were conducted by way of flow field analysis and wind tunnel testing. High pressure recovery throughout the Mach envelope is desirable, because it allows higher propulsion performance and requires a smaller flow duct through the payload section. Wind tunnel testing has taken place to characterize different inlet configurations (Fig. 6).

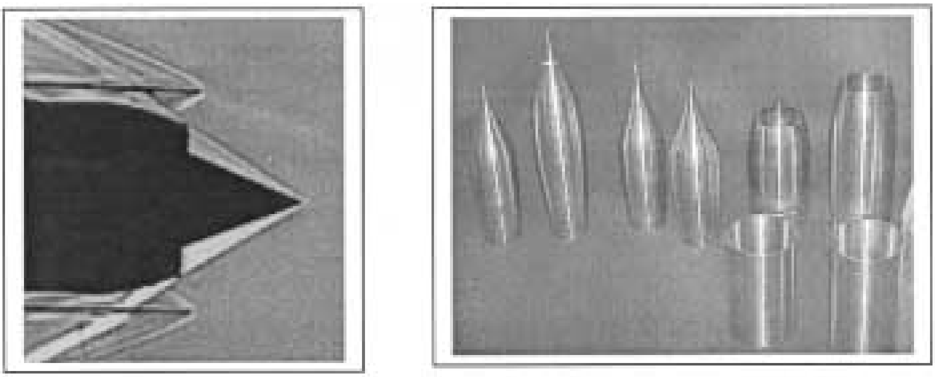


Figure 6. Inlet test hardware.

ACKNOWLEDGEMENTS

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REFERENCES

1. A Stockenström, "Numerical Model for Analysis and Specification of a Ramjet Propelled Artillery Projectile", *Proceedings of the 19th International Symposium on Ballistics*, Switzerland, May 2001.
2. F Dionisio and A Stockenström, "Aerodynamic wind-tunnel test of a ramjet projectile", *Proceedings of the 19th International Symposium on Ballistics*, Switzerland, May 2001.