THE DEVELOPMENT OF THE HYBRID ROCKET FOR BLOODHOUND SSC

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1. ABSTRACT

BLOODHOUND SSC® aims to inspire the next generation of scientists, engineers and mathematicians by setting a 1,000 mph land speed record. The vehicle is powered by an EJ200 jet engine and a hybrid rocket. The type of rocket and the oxidiser selection were important safety considerations in the early stages of the programme. The hybrid uses HTP, decomposed by a silver catalyst and an advanced fuel grain based on HTPB (including a small quantity of solid oxidiser and aluminium powder). The 18-inch (457mm) diameter chamber has been developed using a 6-inch (152mm) diameter prototype, supported by computational modelling. The hybrid chamber is the largest to be developed in the UK, producing an average thrust of 111 kN for 20 seconds and a peak thrust of 122 kN. HTP is delivered to the chamber using an up-rated version of the Stentor large HTP pump from the Blue Steel cruise missile. The pump is driven by a Cosworth V8 Formula 1 engine, which also serves as the vehicle APU. To date, the development programme has included 11 static tests of the 6-inch (152mm) hybrid chamber, 3 static tests of the 44.5 kN monopropellant chamber and a single static test of the 18-inch (457mm) hybrid chamber. High fuel grain regression rates have been achieved, along with uniform regression and exceptional combustion stability. Criteria have also been established for the safety and acceptance testing of the rocket system for use in BLOODHOUND SSC.

2. INTRODUCTION

BLOODHOUND SSC is powered by an EJ200 jet engine from Eurofighter Typhoon and the largest hybrid rocket to have been developed in the UK. The technical challenge of designing a vehicle which can achieve 1,000 mph (1,610 kph) on land is very substantial, in terms of both aerodynamic design and propulsion. These challenges are being used to highlight key aspects of the curriculum through an education programme, which now includes over 5,000 schools, colleges and universities in the UK.

Figure 1: BLOODHOUND SSC

The primary objective of the programme is to address the shortage of engineers and scientists, by producing an iconic project to inspire the next generation to consider careers in these areas. Richard Noble OBE is the project director and Wg Cdr Andy Green OBE (the current land speed record holder) is the driver.

After an extensive evaluation of solid and liquid propellant systems, a hybrid rocket was selected as the preferred candidate. The next stage was propellant selection, Liquid Oxygen, Nitrous Oxide and Nitric Acid were all considered, before final selection of 87% High Test Peroxide (HTP). A HTPB based fuel grain was chosen after a selection process which included PBAN and PVC.

3. 6-INCH (152MM) CHAMBER

Prior to development of the full size chamber a 6-inch (152mm) diameter research chamber was produced. A modest specific impulse target of 200 sec was set early in the programme to ensure that the vehicle performance estimates were based on conservative rocket performance.

The Mk1 version has an aluminium combustion chamber. Eleven static tests of the 6-inch (152mm) chamber have been conducted to date. The objectives were to refine the:

- Fuel grain geometry
- Fuel grain composition
- Catalyst pack, and
- Thermal insulation
The catalyst pack is located at the top of the combustion chamber and consists of 80 silver plated nickel gauzes, similar to the type used in the Gamma series of rocket engines used in the British Black Arrow launch vehicle. The general arrangement of the 6-inch (152mm) chamber is shown in Figure 2.

The 6-inch (152mm) chamber has proved to be an excellent development tool. Early tests focused on the length of the fuel grain and post fuel grain mixing chamber. A conventional 9-point star configuration was selected for the fuel grain. The use of a small percentage of ammonium perchlorate and various burning rate modifiers in the fuel grain, combined with careful control over the fuel grain density, allows high regression rates to be achieved. The fuel grain composition was also tailored to provide a rough surface during the firing, this promotes local turbulence improving mixing and entrainment. Two of the static tests (006 and 008) resulted in chamber failures. Both failures were associated with the thermal insulation around the catalyst pack/fuel grain interface. Additional silica phenolic insulation was added in this area and this performed well in subsequent firings.

The Mk2 chamber is currently under development, it has a carbon fibre combustion chamber, an inconel catalyst pack body/injector and a lightweight nozzle.

\[ \rho_s r_b = A_i \exp\left(\frac{-E_a}{R_u T}\right) \]

where \( r_b \) is the fuel grain regression rate, \( \rho_s \) is the fuel grain density, \( R_u \) is the universal gas constant, \( T \) is the surface pressure and \( E_a \) and \( A_i \) are empirical constants. These constants can be obtained for HTPB from the works of Brill[i] or Cohen[ii].
The energy balance which must be solved can be written as

\[ -\kappa \frac{\partial T}{\partial y} = Q_{\text{cond}} \]

where \( \kappa \) is the thermal conductivity of the gas at the surface of the fuel grain, \( y \) is the direction perpendicular to the grain surface, and \( Q_{\text{cond}} \) is the heat flux being conducted away from the surface into the fuel grain. The conduction term can be calculated by an external FEM or if the fuel grain is assumed to be thick and heat fluxes are not varying too quickly in time, a steady state assumption can be used to simplify the calculation of \( Q_{\text{cond}} \) such that

\[ Q_{\text{cond}} = \rho_s r_s (H_f - H_{300}) \]

where \( H \) is the enthalpy of the solid fuel grain. The subscript \( T \) represents evaluation at the surface temperature while the subscript 300 represents evaluation at the ambient temperature (300K). The full simplified energy balance can then be written as

\[ -\kappa \frac{\partial T}{\partial y} = A_s \exp\left(-\frac{E_a}{R_s T}\right)(H_f - H_{300}). \]

This is the form of the energy balance equation implemented within TINA in support of the BLOODHOUND SSC project.

The mass balance that must be solved can be written as

\[ \rho_s r_s X_{\text{pyrol}} = A_s \exp\left(-\frac{E_a}{R_s T}\right) X_{\text{pyrol}} = -D \frac{\partial Y}{\partial y} + v_g \rho X \]

where \( X_{\text{pyrol}} \) are the pyrolysis gas species mass fraction, \( Y \) are the gas phase species mole fractions, \( D \) are the gas phase diffusion coefficients, \( X \) are the gas phase species mass fractions and \( v_g \) is the gassing velocity. The gassing velocity is calculated using mass conservation such that

\[ \rho v_g = \rho_s r_s. \]

Equations (4) and (5) are iterated using a Newton Raphson scheme to solve for \( T \) and \( Y \) (all other surface variables can be calculated from these).

This treatment of the oxidiser/fuel grain surface interaction was used to assess rocket motor performance to support the 6-inch (152mm) prototype configuration. In this example, we were required to simulate performance near the start of the fuel grain burn. Computational resources and time constraints were such, that only two dimensional simulations were possible. In order to address this problem, an equivalent two dimensional geometry relevant to the start of the fuel grain burn was used. The equivalent geometry was chosen so that the following physical properties were matched with the real geometry:

- Exposed fuel grain area (start of burn)
- Fuel grain inflow area
- Nozzle expansion ratio
- Nozzle exit plane area

In order to match these properties in 2D, an annular combustion chamber and nozzle were modelled. The inner wall of this configuration is inviscid (i.e. does not contribute to thermal and viscous losses). Since the mixing chamber had been identified as an important contributor to motor performance, a mixing chamber was added before the nozzle. The outline for this representative geometry is given in Figure 4.

![Figure 4: Representative 2D geometry](image)

Details of the temperature map obtained through the nozzle and mixing chamber are given in Figure 5.
Fuel vapour is liberated from the fuel grain surface and mixes with the inflowing oxidiser to create a flame (region of high temperature) above the surface. A circulation region exists within the mixing chamber further mixing fuel and oxidiser. In this simulation, the oxidiser is High Test Peroxide which is assumed to fully decompose to gaseous \( \text{H}_2\text{O} \) and \( \text{O}_2 \). As such, a treatment of two phase spray modelling was not required. As can be seen, the CFD treatment of this problem explicitly models the flow of oxidiser through the fuel port, the development of a boundary layer over the fuel grain (including mass addition effects), the liberation of fuel from the fuel grain, the mixing of oxidiser and fuel and the combustion of fuel. These coupled phenomena are very challenging to model using approximate engineering treatments.

Delivered thrust is assessed by integrating inertial (mass flow rate multiplied by velocity) and pressure contributions across the nozzle exit plane. The thrust from this modelling exercise agreed very closely (within 1%) with the average thrust for the test firing measured by The Falcon Project. However, the configuration modelled here was representative of conditions near the start of ignition where the instantaneous measured thrust was considerably higher. Further development is required to refine the model in order to produce a design quality prediction tool.

At the conclusion of this short study, the following areas were prioritised for model development to improve agreement with available experimental data:

- Two phase flow (modelling of aluminium additives). Significant capability in this area already exists within TINA (baseline capability already available).
- Radiation transport to fuel grain (this has been suggested as important in other CFD studies\[iii\] of hybrid combustion)
- Rough wall effects (enhanced surface area / turbulent heat transfer augmentation)

### 5. Pump Development

The BLOODHOUND HTP pump was developed from the large HTP pump from the Stentor rocket engine, used in the Blue Steel cruise missile, which was carried by the RAF’s V-Bombers in the 1960’s. The design was reverse engineered with the assistance of one of the original designers, as engineering drawings were not available. The design of the volute was improved to provide the increased performance required for BLOODHOUND. The outline specification is as follows:

- Inlet Pressure: 0.165 MPa
- Outlet Pressure: 7.58 MPa
- Pump Speed: 11,000 rpm
- Flow Rate: 47.6 kg/sec
- Mass: 23 kg

The initial development work was done on a heavy cased Mk1 version, this was run extensively on a water test rig to establish that the pump met the performance requirements. The weight of the pump was subsequently reduced, by redesigning the housing to produce the Mk1.5 version, which will be used on the car. A sectioned model of the Mk1.5 is shown in Figure 6. The pump has a 5 bladed impeller and a 3 bladed axial inducer. The Mk1.5 HTP pump was the first manufactured part of BLOODHOUND SSC.
The original Stentor pump was powered by a single stage, 50,000 rpm, impulse turbine, driven by HTP decomposers. This approach was considered for BLOODHOUND, however it was decided that a piston engine was the preferred option. A Cosworth CA2010, V8, Formula 1 engine was selected, this engine provides 800 hp and also serves as the vehicle auxiliary power unit (APU). The V8 runs at around 18,000 rpm and drives the pump through a reduction gearbox.

The fuel grain has a mass of 181 kg and a 9-point star central conduit. The fuel grain is automatically ignited by the temperature of the decomposition products from the catalyst pack. The outline specification for the system is as follows:

- Total Impulse: 2,230 kN.sec
- Burn Time: 20 seconds
- Ave. Thrust: 111 kN
- Max. Thrust: 122 kN
- Target ISP: 200 sec
- Current ISP: 239 sec
- Total Propellant Mass: 1,130 kg
- O:F Ratio: 5.25:1

To date a single, pressure fed static test has been conducted. This low pressure test confirmed the fuel grain regression rate was as predicted. Based on data from the 6-inch (152mm) programme and the modelling, the composition of the fuel grain has been tailored to suit the local dynamic conditions along the length of the chamber. This has produced very uniform regression along the length of the fuel grain.

Once the development firings of the Mk1 chamber are complete, production of the Mk2 chamber will begin. The Mk2 is essentially a lightweight version of the Mk1. The design of the Mk2 chamber is progressing well and it includes many of the features (such as a carbon fibre combustion chamber), which are currently being tested on the Mk2 6-inch (152mm) chamber.
7. Test Programme

The test programme is split into two stages, the Research and Development phase and the Safety and Acceptance Testing phase. The R&D phase includes all the development firings and will conclude with 2 full duration, full thrust, static firings, to ensure the system meets the performance requirements.

The S&A testing programme has been developed to provide sufficient confidence in the system to enable it to be used in BLOODHOUND SSC. The S&A programme has been drawn up with the support of Rainham Industrial Services Ltd who are a BLOODHOUND sponsor and an industrial services company, specialising in high hazard industries. The project is also working with the UK Health and Safety Executive, to help underline their message of sensible risk management. The S&A phase will include 5 full duration, full thrust static firings. It will also include a number of tests beyond the operational limits of the system and individual testing of key components and sub-assemblies. Most importantly, it will continue during the running of BLOODHOUND SSC, as the dynamic inputs to the system will not be known until the car reaches high speeds (i.e. above 700 mph/1,130 kph).

8. The Next Stage

The next stage of the programme is the integration of the various components of the BLOODHOUND propulsion system, specifically the combustion chamber, HTP pump, HTP tank, nitrogen pressurisation system, V8 engine and control system. There will be a number of short duration pump fed monopropellant trials before the first pump fed hybrid firing, which will take place in the UK in summer 2012. It will be the largest rocket to be static tested in the UK for around 20 years.

BLOODHOUND SSC will be complete in early 2013, there will be some low speed (200-250 mph/322-402 kph) testing on a runway in the UK, before the team head to South Africa. The run site which has been selected is Hakskeenpan in the Northern Cape of South Africa. A 12 mile (19.3 km) long track is required for the running of the car, work on the track has been underway for a number of years with the support of the Northern Cape Government. The car has always been envisaged as a rolling laboratory, to validate the predictions made using CFD by Swansea University and BLOODHOUND’s Aerodynamicist Ron Ayers. There will be a number of runs in an incremental programme to gradually increase the speed. The objective of the runs in 2013 is to break the current record. The team will return in 2014 and endeavour to push the record to 1,000 mph. Immediately after each run all the data from the car will be available to the students and public following the project around the world.

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