Progress towards a 1.1 kN apogee engine for interplanetary propulsion

Space Propulsion 2012, Bordeaux, France

L. Naicker[1,4], A. Baker[3,5], I. Coxhill[1,6], J. Hammond[1,7], M. Houston[1,8], D. Perigo[2,9], N. Solway[1,10], R. Wall[1,11]

[1]AMPAC-ISP Europe, 15 - 16 Northwest Business Park, Ballycoolin, Dublin 15, Ireland
[2]European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[3]Kingston University, River House, 53–57 High Street, Kingston upon Thames, Surrey KT1 1LQ, United Kingdom

ABSTRACT

AMPAC-ISP Europe has been contracted by the European Space Agency (ESA) to perform Combustion Chamber and Injection Technology Development in the first phase of a multi-phase programme to develop and qualify a new all-European bi-propellant High Thrust Apogee Engine (HTAE) for Mars exploration. Further objectives will be to tailor the HTAE in form, fit, performance and cost suitable to next generation commercial spacecraft requirements.

The paper summarises Phase 1A of the development programme which has concluded with a baseline design targeting a normal design point vacuum thrust of 1.1 kN at a minimum vacuum specific impulse of 321 s.

Keywords: Mars, apogee, hypergolic, MREP

INTRODUCTION

There is presently a lack of off-the-shelf propulsion hardware in Europe to support ESA's space exploration projects. These market gaps potentially allow ESA money to flow outside member states.

Past propulsion development activities were only initiated by ESA at Phase B2 or C, leaving propulsion on the critical path. The strategy now being pursued by ESA is to initiate a number of technology pre-developments to establish technical credibility and maturity. This allows future programs to evaluate these technologies sufficiently early [1].

The High Thrust Apogee Engine (HTAE) is one such development initiated to evaluate the benefits of a high thrust engine for the European Mars Robotic Exploration Program (MREP).

For current large missions, consistent with maximum payload capabilities of Ariane 5, studies show [2] propellant throughput is increased by some 200 to 300 kg due to work done against the Martian gravitational field during orbit insertion. This equates, directly, to a reduction in bus and payload mass.

Figure 1 shows the propellant mass savings for a 1000 N engine compared with a current 500 N engine, for a range of spacecraft hyperbolic arrival velocities and masses, ahead of Mars Obit Insertion (MOI). [2]

The points on the graph refer to the maximum pre-MOI spacecraft masses and associated hyperbolic arrival velocities for an Ariane 5 mission for a variety of dates. Only missions via direct escape trajectories are assumed to be able to arrive at Mars with sufficient mass to be of interest. The plot shows that the higher the hyperbolic arrival velocity and pre-MOI mass, the higher the

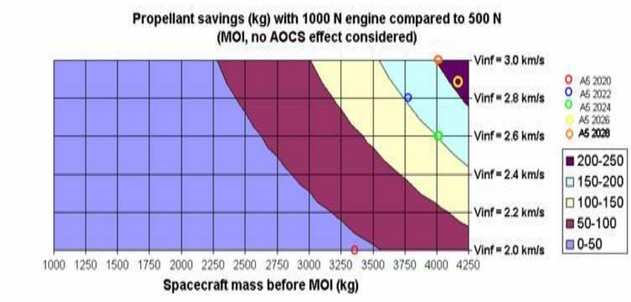

Figure 1: Propellant mass savings with a 1000 N engine compared to a 500N engine [2].

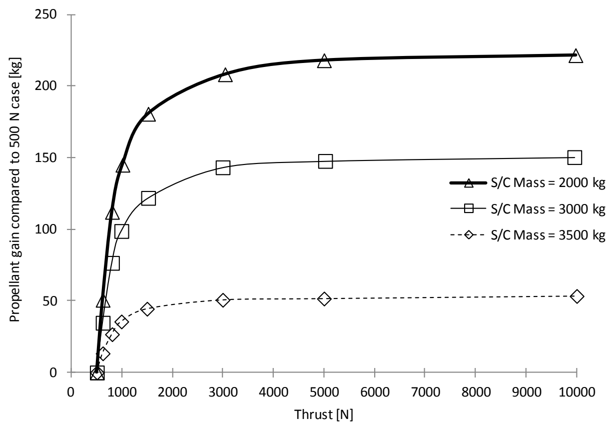

Figure 2: Reduction of propellant use compared to a 500N engine [2].

[4]Propulsion Engineer, Technical Lead, AMPAC-ISP Europe, Westcott division, United Kingdom, lnaicker@ampacisp.eu
[5]Materials Engineering Consultant to AMPAC-ISP Europe
[6]Chief Engineer, AMPAC-ISP Europe, Westcott division, United Kingdom
[7]CAD Design Engineer, AMPAC-ISP Europe, Westcott division, United Kingdom
[8]Valve Design Engineer, AMPAC-ISP Europe, Dublin division, Ireland
[9]Chemical Propulsion Engineer, TEC-MPC Propulsion and Aerothermodynamics Division, ESA-ESTEC
[10]Structural Engineer, AMPAC-ISP Europe, Cheltenham division, United Kingdom
[11]Project Manager, AMPAC-ISP Europe, Dublin division, Ireland

propellant mass saving.

Figure 2 shows that the majority of gravity loss recovery can be achieved with a 1500 N engine and that engine thrust levels above 3000 N are of diminishing return.

An HTAE in the range 1.0 to 1.5 kN with current State-of-the-Art (SoA) specific impulse of approximately 320s would be of significant benefit for future missions by minimising gravity losses for planetary orbit insertions.

ENGINE OVERVIEW

Figure 3 shows the Phase 1A baselined HTAE. The engine uses Mono-Methyl Hydrazine (MMH) as a fuel and Di-Nitrogen Tetroxide with 3% Nitrogen Monoxide (MON-3) as an oxidiser. Given a Normal Design Point (NDP) propellant feed pressure of 1.54 MPaA, it is designed to produce a vacuum thrust of 1100 N with a minimum vacuum Specific Impulse (Isp) of 321 s at a Mixture Ratio (MR) of 1.65.

In order to maintain the Attitude and Orbit Control System (AOCS) engine to main engine thrust ratio of current 500 N main engines (10 N / 500 N) the HTAE Nominal Design Point (NDP) thrust has been set to 1100 N, allowing use with off-the-shelf 22 N attitude control thrusters, and thus maintaining similar torque margins[2].

The lower bound thrust of the HTAE has been set to 900 N and is an estimate of future telecommunications platform acceleration load tolerances for deployable structures such as solar arrays which are usually partially deployed prior to the apogee engine burn. The upper bound thrust is taken as 1300 N to balance the thrust range.

The HTAE is an evolution of the LEROS range of apogee engines. One important evolutionary change has been made at the injector head assembly where the valves have been orientated at 0 and 90^{o} relative to the mounting flange. This change improves engine reliability by reducing the number of sealing interfaces to a single surface per valve at the engine-valve interface. The mechanical interface for engine and valve mounting as well as the electrical interface for valve and flange heaters are maintained in accordance with other LEROS production engines.

The size of the expansion nozzle exit-to-throat area ratio has been set to 293:1 and is limited by preliminary estimates of the platform and launcher envelope constraints.

The total mass of the baseline engine is approximately 10 kg, with the possibility of reducing this to 6.5 kg by using an alternative material for the expansion nozzle.

Engine heritage has been maintained most notably with the choice of an all-welded assembly, surface contouring, and injector manifold layout.

To ensure that the HTAE is compatible with European apogee engine valve technology, a valve development programme is being undertaken within AMPAC-ISP.

The baseline materials for the engine assembly are

i. Ti-6AL-4V for the injector head, distribution ring and injector plate,
ii. C103/R512E for the combustion chamber,
iii. C103/R512E for the expansion nozzle with an option of using a Ti-6AL-4V.

This choice of materials is considered to be a low risk

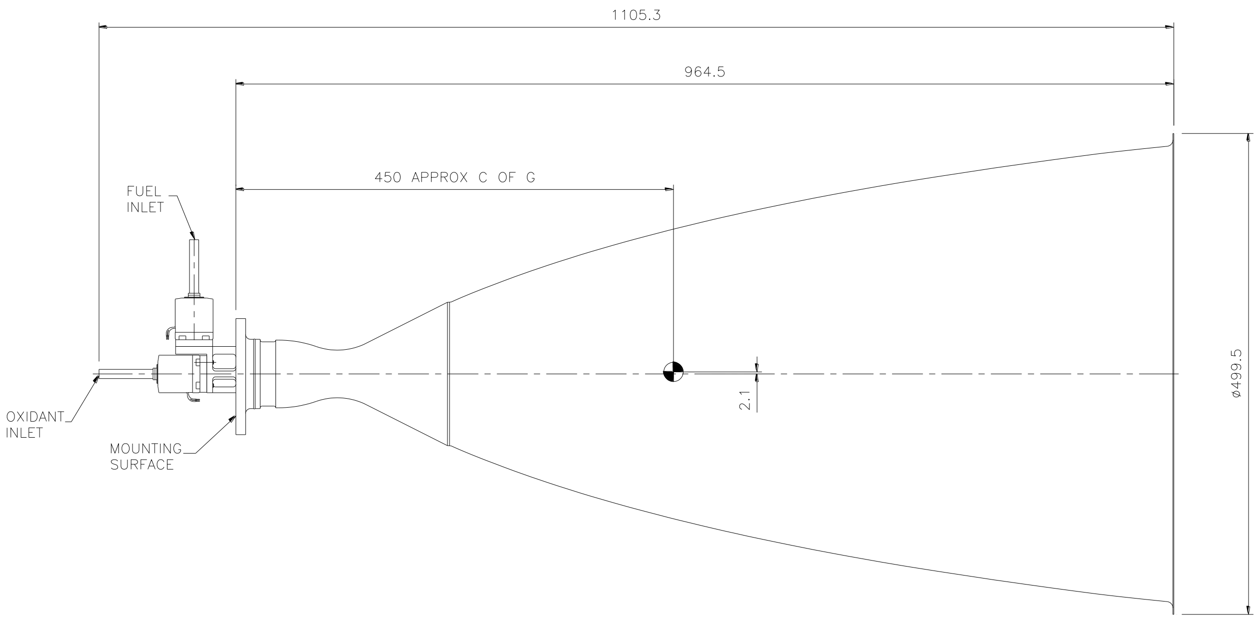

Figure 3: Baseline HTAE dimensions.

option which would be capable of meeting the lower performance high thrust requirements of planetary missions.

MATERIALS

In order to achieve the higher performance (in the region of 323s) and lower thrust requirements for commercial use, the engine is expected to operate with a wall temperature approximately 200K above the LEROS range of engines.

A number of chamber material options are being investigated in Phase 1B of the project to allow higher thermal capability. These are being investigated on the basis of creep strength, oxidation resistance and a number of other factors such as European availability, price and flight heritage:

1. High temperature noble metal (Pt/Rh)

Pt alloyed with Rh and/or Ir material does not require an anti-oxidation coating, has demonstrated performance up to 1600°C, and has considerable flight heritage on the Astrium GmbH S400-12 and -15 400N apogee engines [3].

AMPAC-ISP have both machining and joining experience with Pt/Rh on past engine development projects. Pt/Rh has the most heritage and lowest risk, although a number of issues need to be resolved. These include:

i. High cost and variation with market conditions,
ii. Low creep strength at high operating temperatures,
iii. Cannot be joined (welded) to AMPAC's current Ti-6Al-4V injectors.

Addressing joining issues using expertise at TWI, and creep strength by possibly Ir alloying and/or dispersion hardening will be addressed in Phase 1B.

2. Monolithic Ceramic (Silicon Nitride)

Sintered silicon nitride or Si_3N_4 developed by Kyocera has been formed, ground and qualified into a thrust chamber assembly for the Akasuki or Planet-B mission by Mitsubishi Heavy Industries MHI, under funding from JAXA [4]. This engine material gained flight heritage on Akasuki although suffered catastrophic failure due to off-nominal operation of other propulsion system components.

The qualified engine has been tested by extended hot firing to 1200°C, and for brief periods of 60s to 1500°C. The material has a considerably lower density than C103, and does not require anti-oxidation coating. The theoretical maximum temperature is around 1800°C.

AMPAC-ISP is in discussions with JAXA and MHI to source a monolithic combustion chamber for hot-fire testing in Phase 1B. Issues which need to be resolved are:

i. Uncertainty in thermo-mechanical properties above 1500°C for extended duration firings.
ii. The large size of the HTAE coupled with difficulties in non-destructively identifying critical flaws in the ceramic suggests that the expansion nozzle needs to be a different material. Joining silicon nitride to a metallic injector head assembly will also be required.
iii. Although the raw ceramic material is inexpensive, processing represents a cost uncertainty at present.

The Akasuki engine used a bolted joint between the injector and thrust chamber assemblies. Vapour deposition of a refractory metal such as Nb on the ceramic thrust chamber assembly may allow for welding to a metallic injector head assembly and expansion nozzle, thus maintaining the all-welded philosophy of the LEROS range. AMPAC-ISP intends to test coupon samples to gain confidence in a design approach using monolithic ceramics at this large size.

3. Composite (C/SiC)

Carbon has very high temperature strength, and if protected from oxidation by SiC, can enable an uncooled operation in the temperature range required by the HTAE. Both Astrium GmbH and Snecma Propulsion Solide (now Herakles) are manufacturing bipropellant thruster nozzles, for the 500N class European Apogee Motor (EAM), and for the RL-10 and Vinci (Ariane 5 upper stage) nozzle extensions respectively. This material can be manufactured by one of two chemical vapour or liquid infiltration processes into a carbon fibre pre-form, which is then densified and sealed by Chemical Vapour Deposition (CVD) of SiC. C/SiC composite has a low density, is mechanically very robust, can be manufactured at very large scales, and has demonstrated durability for up to 25hr above 1700°C nozzle wall temperature at low thrust levels [5].

AMPAC-ISP is in discussions with SPS/Herakles to source a C/SiC chamber for hot-fire testing in Phase 1B.

Issues to be resolved with this material are:

i. Scale-up from demonstrated properties at lower thrust levels,
ii. Joining the composite to a metallic injector (the chamber and expansion cone are expected to be one piece). Joining challenges are similar those of Si_3N_4,
iii. Cost of the material. Although the precursor elements are inexpensive, the process of vapour

deposition / infiltration is slow, which is expected to drive up manufacturing costs.

4. Refractory metal and novel coating

All of the previous material combinations (1) to (3) pose significant challenges, and take AMPAC-ISP away from its strong heritage in Nb based coated combustion chambers and nozzles. A programme funded by the UK Space Agency has recently begun, with the objective of developing a high temperature oxidation resistant coating for Nb alloys. This will explore CVD manufacture of robust coatings based on Ir which has very high temperature capability, and coupled with interlayers it can:

i. prevent oxygen diffusion into the underlying substrate,
ii. offer a compliant layer to prevent any expansion mismatch between coating and substrate and
iii. discourage formation of brittle inter-metallics between substrate and coating.

Coating manufacture will be carried out over the next 6 months, and will be characterised by SoA materials science facilities at the University of Manchester. In parallel an effort to source a vacuum cast Nb alloy with equivalent performance to C103 will take place.

These four materials options will be narrowed to a baseline, low risk and a backup, high risk option within the first 6 months of Phase 1B of development.

With the use of any of these high temperature materials the HTAE can be made into an all-European engine.

OVERALL DESIGN METHODOLOGY

The LEROS apogee engine heritage is a combination of:

i. Manufacturing know-how e.g. knowledge of manufacturing challenges, reproducibility, cost effectiveness,
ii. Hardware and engineering drawings that provide an understanding of the design details of a well performing engine, for different propellant combinations and performance targets,
iii. Knowledge of engine performance (transients, steady state, thermal-structural, materials capabilities).

The design methodology chosen for the HTAE implements two approaches to leverage this know-how: a traditional rocket engineering approach, and a more modern version of it that utilises new computational tools.

The traditional approach uses fundamental, 'tried and trusted' design methods that are considered of sufficient accuracy to progress the design to a stage where it can be hot-fire tested. These methods are first applied to existing LEROS engines in order to validate the calculation method before they are considered sufficiently predictive to use for the HTAE design.

Modern design tools such as Commercial-Off–the-Shelf (COTS) Structural/Thermal and Computational Fluid Dynamics (CFD) packages are also validated against LEROS heritage designs. These tools are used to refine the accuracy of the traditional approach as well as fill in gaps where there are no traditional methods available.

In this way the design methodology produces results that are trustworthy enough to take the design from the theoretical design to actual hardware that is ready for hot-fire testing.

TRADE STUDY

In order to survey the current state of apogee engine design techniques and to consider many different approaches for achieving design objectives, a trade study as outlined in Figure 4 was conducted on a subcomponent level. As trades are interdependent, i.e. one trade narrows the scope of another; the trade space was first prioritised according to the following chosen criteria:

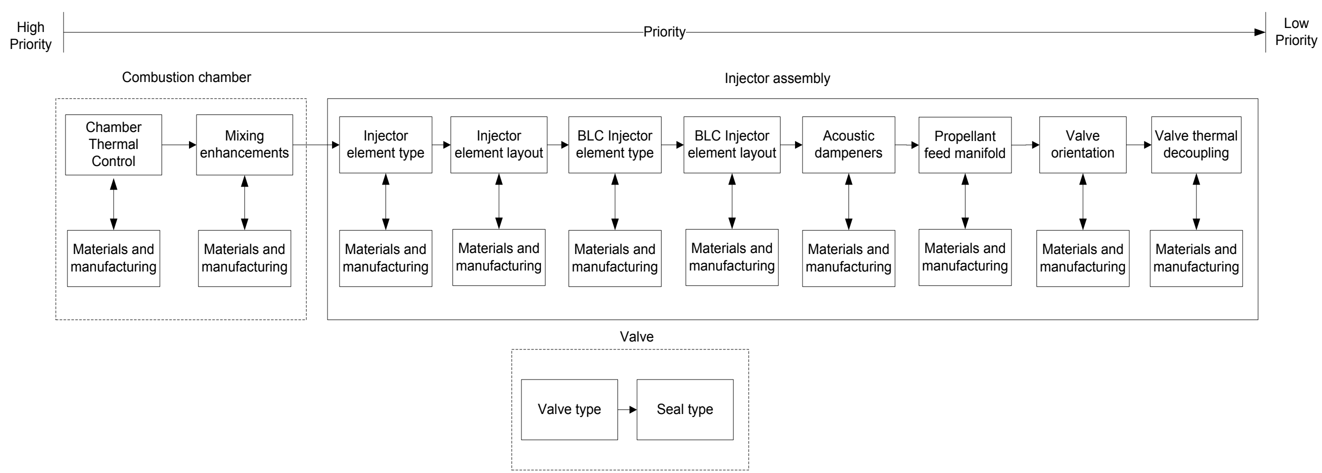

Figure 4: Trade space prioritisation map. Combustion chamber trades are performed ahead of injector assembly trades. Valve trades are considered independently.

i. The trades influence on the propellant feed condition and working environment,
ii. The trades influence on the characteristic velocity C*.

Trades were conducted in a formal weighting and scoring manner. The goal, as far as possible at this stage in the trade study, was to trade criteria that are performance related, and resist a natural bias towards heritage approaches.

Highly scored options from each trade were sorted according to distance from in-house expertise, as a measure of development duration.

Options were then selected from each subcomponent category and combined to build up an Engine Option (EO) i.e. an engine assembly. Based on the duration of development work required on the subcomponents, each EO was further ranked, the most conservative of which formed the baseline engine. The development plan starts with the testing of this engine and moves on to less conservative EOs should the baseline engine not meet the requirements.

Trade studies were conducted in a cautious manner as complete objectivity can never be guaranteed. At the very least, the study is considered a structured thinking and justification aid that verbosely records the complex decision making process leading to the choice of one trade option over another. This allows all stakeholders to be clear on the direction and risks of the project at an early stage.

As an example, some of the trade options considered for the injector elements were

i. Unlike jet-jet impinging doublets (UID)
ii. Like jet-jet impinging doublets
iii. 2-on-1 impinging triplets
iv. Splash plates
v. Combinations

Design Process

The design process for NDP operation focuses on steady-state design issues and is shown in Figure 5. Three paths were followed in parallel; the chamber design, which primarily focuses on bulk mixing phenomena; the injector assembly design which primarily focuses on local mixing; and the pressure network which defines the attainable chamber pressure.

As design calculations are performed using different calculation tools and sometimes in parallel, there is a disconnect at the input/output interface. For instance, the injector assembly calculation is dependent on the pressure network calculation results. They are linked by the chosen pressure drop across injector elements (which is generally specified as a fraction of the chamber pressure), however as the calculation of pressure drop in the propellant feed manifold was performed in CFD, the two have been decoupled and have been performed iteratively.

Injector Head Assembly Design

The detailed calculation of injector diameters was an iterative one that maximises the overall flow coefficient [6]:

$$C_{\mathrm{f,j}} = \frac{1}{\sqrt{1+\xi_{\mathrm{j}}}}$$

$$\xi_{\mathrm{j}} = (\xi_{\mathrm{in}})_{\mathrm{j}} + (\xi_{\mathrm{fr}})_{\mathrm{j}} + (\xi_{\mathrm{1\text{-}c}})_{\mathrm{j}}$$

Where j ϵ [Fuel Core (FC),Oxidant Core (OC),FFC] is the injector type, ξ_j is the total hydraulic loss coefficient, ξ_{in} is the inlet hydraulic loss coefficient, ξ_{fr} is the friction hydraulic loss coefficient, $\xi_{1\text{-}c}$ is the vortex hydraulic loss coefficient, C_f is the overall flow coefficient [fraction], ξ is the total hydraulic loss coefficient [dimensionless].

Its main inputs were

i. injector ΔP as a function of chamber pressure
ii. the number of injector elements

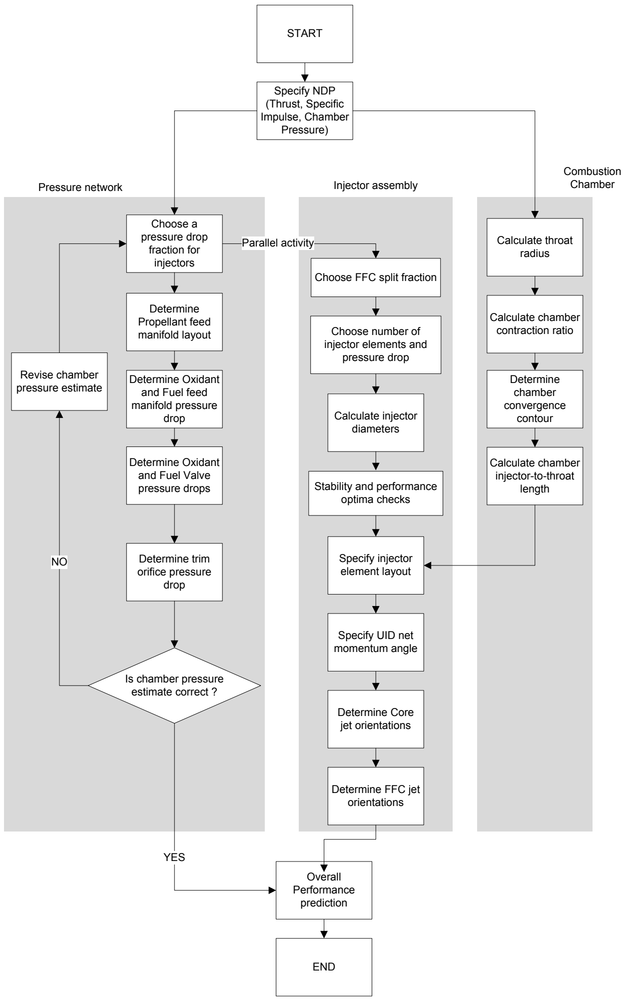

Figure 5: Design process for NDP steady state operation.

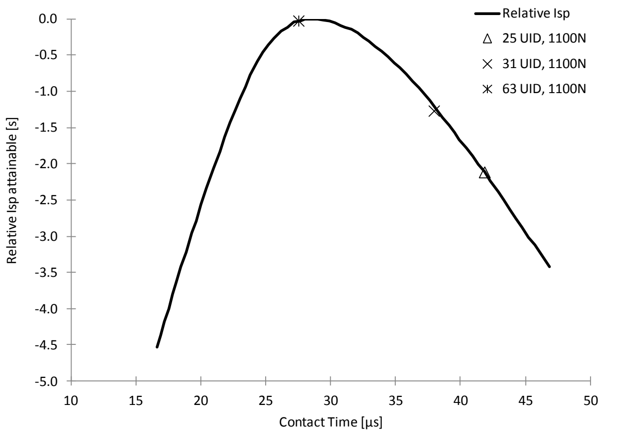

Figure 6: Contact Time as a performance criterion for impinging doublets.

iii. the maximum length-to-diameter ratio allowable by conventional drilling

The choice of these inputs is arbitrary if viewed outside the context of optimisation criteria. Three examples of these

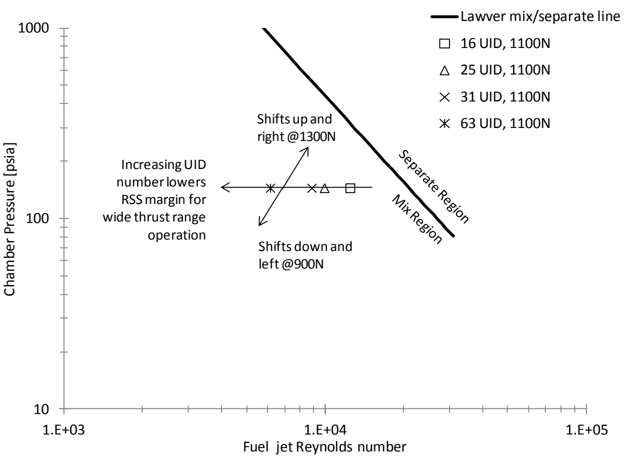

Figure 7: Lawver Criterion for Reactive Stream Separation [9].

criteria, important to UIDs in general and hypergolic impingement in particular, are Contact Time (CT) and the margin for Reactive Stream Separation (RSS).Contact time is a velocity related term which is defined, for a given

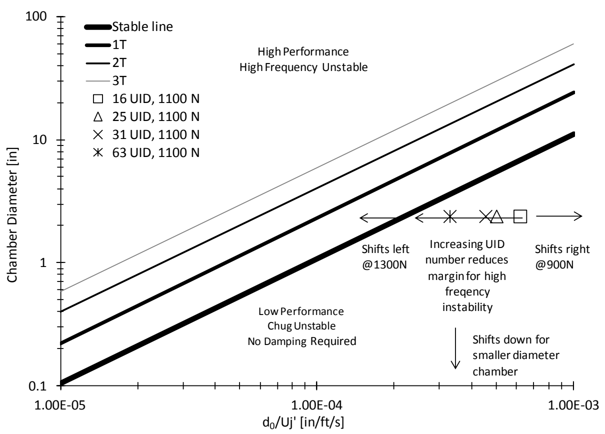

Figure 8: Hewitt criterion for acoustic stability [10].

impingement distance, as the maximum time taken for a molecule in one jet to traverse the second jet in the doublet:

$$\tau = \left(\frac{d_{inj,FC}}{v_{inj,FC}}\right) * 10^{-6}$$

Where τ is the contact time [μs], $d_{inj,FC}$ is the FC injector diameter [m], $v_{inj,FC}$ is the FC injector jet velocity [m/s]. It is referenced to the fuel as the vapour pressure of the fuel is lower than that of the oxidant and therefore rate controlling.

The relationship between CT and Isp (consequently C*) is given in Figure 6. When the number of core injector elements is varied at fixed injector ΔP, contact time is optimised under 'fine propellant injection' (larger number of injector elements) rather than 'coarse propellant injection' (fewer number of injector elements).

Design criteria for unlike doublet injector elements are generally based on non-reactive cold-flow correlations such jet diameter ratio [7] and droplet size [8]. However, for highly reactive hypergolic fuels, the impingement process is disturbed by rapid combustion at the impingement interface known as Reactive Stream Separation (RSS). The gas evolved during rapid liquid phase reaction at the impingement point causes the streams to 'blow-apart' or separate before substantial amount of liquid phase missing can occur. This phenomenon reduces injector efficiency and, if cyclic, leads to acoustic instability.

In the Lawver criterion [9] of Figure 7, RSS is correlated with a vaporisation controlled model by plotting FC jet Reynolds number against chamber pressure. Two distinct regions are defined for UID operation – a mixing and separation region. The plot is once again referenced to the rate controlling fuel side.

The general trend shows that coarse injection is more likely to experience RSS (closer to the stream separation line) than fine injection. As the x-axis is based on Reynolds number, and the y-axis is based on chamber pressure, both of these are expected to increase with increasing thrust and decrease with decreasing thrust. This means that the trend shown is expected to move up and right (towards the separation line) at higher thrust operation of the engine, and down and left for low thrust operation of the engine. Therefore, to reduce the margin for RSS in a wide thrust range engine, finer propellant injection is desired i.e. a greater number of core injector elements. So even through the 16 UID case has the most optimised contact time of all the cases, it is most likely to experience RSS in the high thrust region of engine operation.

The Lawver criterion used to determine RSS for the UIDs correlates instability at the local level i.e. by correlating the injector design and operation (embodied by the jet Reynolds number of the least volatile propellant). Figure 8 shows the Hewitt stability correlation [10] which describes instability in a more global sense, by correlating the injector design and operation (embodied by the injector diameter to jet velocity ratio of the least volatile propellant) as well as the chamber diameter.

The correlation is valid for impinging jet injectors and to both storable and LOX/HC propellant combinations. Above the bold line the engine operates in the high frequency unstable regime and acoustic damping will be required. Thresholds for different Tangential (T) modes of oscillation are also shown in the high frequency unstable region. The correlation indicates that an increase in the stability margin is achieved at the expense of performance.

The competing nature of the Lawver criterion and the Hewitt criterion is evident in Figures 7 and 8.

THRUST CHAMBER ASSEMBLY DESIGN

The HTAE uses the combined thermal control strategy of

i. Liquid Fuel Film Cooling (FFC) as a form of Boundary Layer Cooling (BLC) to reduce steady-state soak back temperature and wall temperature,
ii. A chamber wall external step to reduce heat conduction to the injector assembly and liquid FFC layer,
iii. A throat thermal shunt (increased wall thickness profile) to preferentially conduct heat away from the injector assembly.

Experience at AMPAC-ISP has shown that a parameter, which can be used as a design guide to determine the FFC mass flow rate, while maintaining a homogenous liquid length adjacent to the injector, is the 'FFC peripheral density' defined as follows :

$$G'_{FFC} = \frac{G_{FFC}}{\pi D_c}$$

Where G'_{FFC} is the FFC mass flow rate per unit perimeter [kg/s/m], G_{FFC} is the mass flow rate of FFC [kg/s], D_c is the chamber diameter [m].

Maintaining the same G'_{FFC} value between a 'similar' engine, in this case the LEROS 2b, and the HTAE, results in a FFC split fraction given by

$$S_{FFC} = \frac{G_{FFC}}{G_F} = \frac{\left(G'_{FFC}\right)_{L2b}\pi(D_c)_{HTAE}}{G_F}$$

According to this scaling rule, the larger the chamber diameter the more FFC is required to cool the wall, reducing the amount of fuel available for efficient core combustion and decreasing C*.

Decreasing the amount of fuel used for FFC at fixed chamber diameter, increases face and flange temperature. As FFC is reduced there is eventually a step transition in flange temperature due to a transition from nucleate to film boiling of the FFC layer as throat temperature increases and conducts up the chamber to the liquid FFC region.

The design goal therefore is to optimise towards smaller chamber diameter.

Both the throat thermal shunt and the external chamber thermal step are optimised in ANSYS based on estimated thermal boundary conditions.

STRUCTURAL AND THERMAL ANALYSIS

The scaling rules used to determine the combustion chamber geometry concentrate on flow related phenomena which define the 'wetted' geometry of the engine. To determine whether the engine structure is capable of maintaining this geometry, given pressure and thermal loading experienced under normal and off-nominal operation, requires combined structural and thermal analyses of a chosen wall thickness profile (which defines

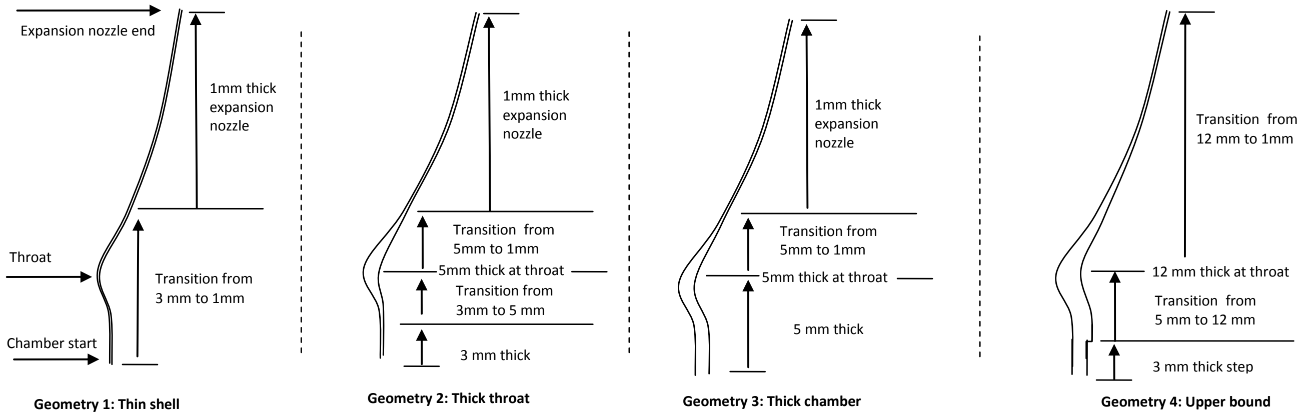

Figure 9: Four HTAE thrust chamber assembly geometries investigated in ANSYS 14.0

the external geometry).

A series of case studies were performed using the structural and thermal analysis package ANSYS v14.0. The goal of these case studies was to study the interrelationship between

i. engine mass,
ii. outer wall geometry,
iii. Margin Of Safety (MOS),
iv. natural frequency,
v. soak back temperature

The approach used was to build a 2-D axis-symmetric geometry within ANSYS to represent the combustion chamber and then tailor this according to the requirements for a particular case study. Steady-state structural analyses were performed to determine the MOS given imposed thermal and pressure profiles. Transient thermal and modal analyses were then performed on a revolved axisymmetric geometry mated to the injector assembly.

Table 1: Margin Of Safety (MOS) and natural frequency results for four HTAE thrust chamber assembly geometries investigated in ANSYS v14.0

		Minimum Margin of Safety*			
Study	Name	Geometry 1	Geometry 2	Geometry 3	Geometry 4
1	Steady State (LB)	0.85	0.58	0.24	0.098
2	Steady State (Exp)	—	—	—	—
3	Steady State (UB)	-0.33	-0.59	-0.62	Expected negative
4	Shutdown Transient (LB)	0.68	0.47	0.17	0.087
5	Shutdown Transient (Exp)	0.323	0.134	-0.129	-0.503
6	Shutdown Transient (UB)	-0.37	-0.61	-0.63	Expected negative

* Factor of Safety (FOS) is 1.25 in all cases except for the Exp temperature studies where it is 1

	Geometry 1	Geometry 2	Geometry 3	Geometry 4
Natural Frequency [Hz]	17.4	22.6	24.6	33.97

Figure 9 shows four geometries that were studied.

i. Geometry 1 represents an attempt to find the lower bound mass of the engine i.e. the approach to the material yield strength.
ii. Geometry 2 was used to investigate the influence of throat thickness on natural frequency and stress.
iii. Geometry 3 was used to investigate the influence of overall chamber thickness on natural frequency and stress.
iv. Geometry 4 was used to investigate an upper bound wall thickness profile.

Table 1 shows the preliminary MOS results for all four geometries as studied in the two scenarios of steady state operation (application of both a temperature and pressure boundary condition) and shutdown transient (application of only an initial temperature condition). Three different thermal profiles were used with approximate peak temperatures of 1600K, 1800K and 1900K corresponding to Lower Bound (LB), Expected (Exp), Upper Bound (UB)

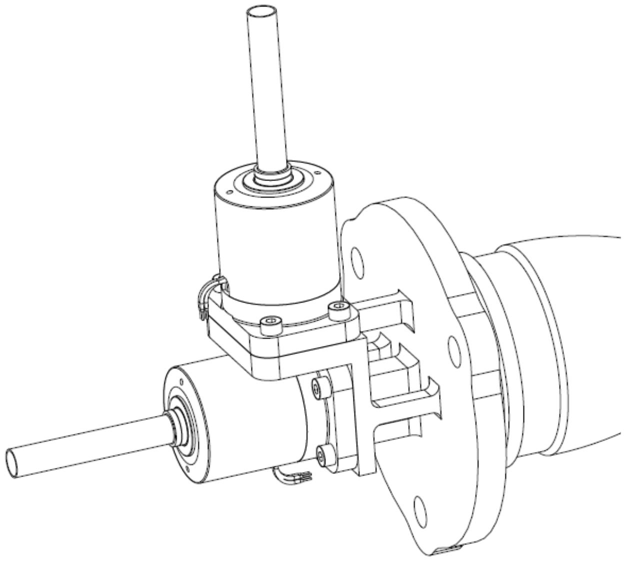

Figure 10: HTAE injector assembly showing the preliminary valve design.

respectively and occurring near the convergent section of the chamber.

In all geometries the maximum stress (and minimum MOS) occurs for the shutdown scenario at the converging section of the chamber where there is high thermal stress (and therefore low material strength). It does not occur for the steady-state study (pressurised case) because the higher pressure at the upstream end of the chamber increases the chamber diameter to relieve a thermally expanded geometry at the throat. The preliminary results show chamber geometries 1 and 2 do not yield for C103 material at the Exp thermal profile.

The price to be paid for such thin walled structures is a lowering of the lowest dominant resonance frequency as shown in the preliminary modal analysis results in Table 1.

The mode of vibration for all cases is one where the expansion nozzle bends about the throat. As chamber wall thickness increases from Geometry 1 through to 4, the lowest dominant resonance frequency shifts upward. The study shows that natural frequency requirements above 30Hz are difficult to meet for an apogee engine.

Also noticed is that there is no significant benefit in attempting to reduce wall thickness in order to reduce engine mass. Any reduction in engine mass will need to come from the use of a different expansion cone material such as Ti-6Al-4V.

VALVE DESIGN

As there are no low pressure drop valves available in Europe for this class of engine, AMPAC-ISP has performed a design study on a solenoid actuated valve for HTAE application. Figure 10 shows these valves mounted to the injector head assembly.

The following parameters were studied given a constraint on the valve footprint (51mm x 38.1mm):

i. The valve pressure drop at NDP,
ii. The force margin at Beginning of Life (BOL) for NDP feed pressure of 1.54 MPaA, for low thrust feed pressure of 1.2 MPaA, for high thrust feed pressure of 1.9 MPaA.

Preliminary estimates show a pressure drop of 0.325 ΔMPa at a water equivalent flowrate of 0.18 kg/s and a BOL force margin of 37% at NDP feed pressure which is in the region of what is typically acceptable on apogee engine valves. The force margin at the high and low thrust operating point is expected to be 27% and 47% respectively. The estimated mass of the HTAE-compatible conceptual apogee engine valve is 0.42 kg.

CFD ANALYSIS

The pressure drop between propellant feed and combustion chamber is the sum of the pressure drops across the trimming orifice, propellant valve, and injector assembly. There are two such networks, one for the fuel and one for the oxidant. The boundary condition at the upstream point is the fuel and oxidant feed pressure. The boundary condition at the downstream point is a common chamber pressure.

Given this pressure network, the K-factor method [11] (and later CFD) was used to estimate pressure drops through the manifold. Combined with the pressure drop of the valve and that allocated to the trimming orifice, the chamber pressure of the engine is estimated at 1MPaA.

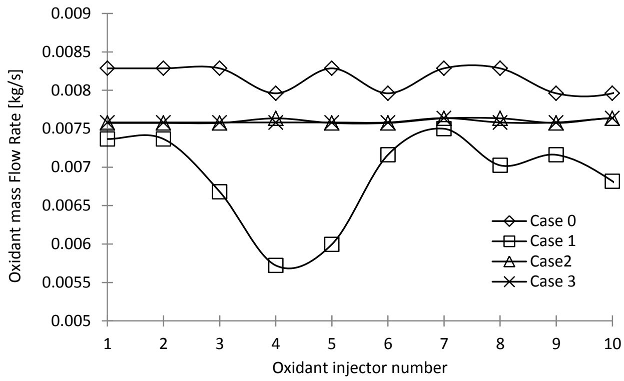

Figure 11: Injector flow optimisation using CFD to obtain uniform flow across adjacent injectors.

Due to the limitation in length-to-diameter ratio offered by conventional drilling of injectors, flow uniformity ahead of injectors is important for optimal UID impingement. A number of propellant feed manifolds were analysed by cold-flow CFD (ANSYS Fluent) to compare flow uniformity as measured by the variation in flowrate between adjacent injectors.

Figure 11 indicates the typical level of optimisation achieved between cases 0 and 3 by optimising the propellant feed manifold upstream of core oxidant injectors.

CONCLUSION

Figure 12 shows the HTAE project divided into 3 phases of duration 2, 3, and 2 year duration respectively.

Phase 1A lasted 12 months and covered in depth investigation of the baseline engine design (Figure 13) for the HTAE. The phase concludes with a Baseline Design

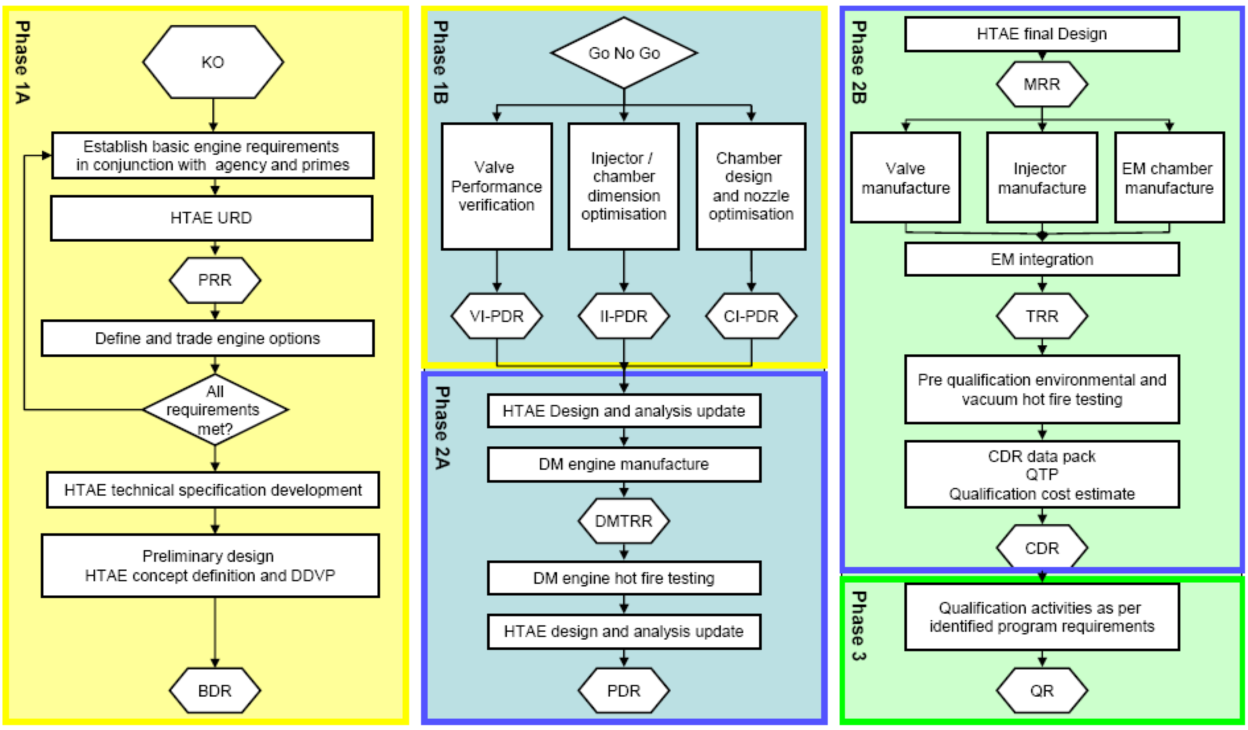

Figure 12: HTAE project phases.

Review (BDR) of the HTAE in May 2012.

A good understanding of the design drivers and sensitivities has been obtained. Based on this understanding a parameter space has been defined for exploration in Phase 1B.

In the ~12 month Phase 1B which follows, the HTAE design will be further iterated, cold flow testing will be performed to screen injectors, and a thermally representative 'flight weight' development model will be manufactured and subjected to hot-fire testing.

ACKNOWLEDGEMENTS

AMPAC-ISP would like to acknowledge the contributions of subcontractors: Djamel Boutamine at Engineering Solutions International Limited (ESIL) in Ireland for CFD analysis and Calvin Prentice at Archer Technicoat Limited (ATL) in the UK for the materials study.

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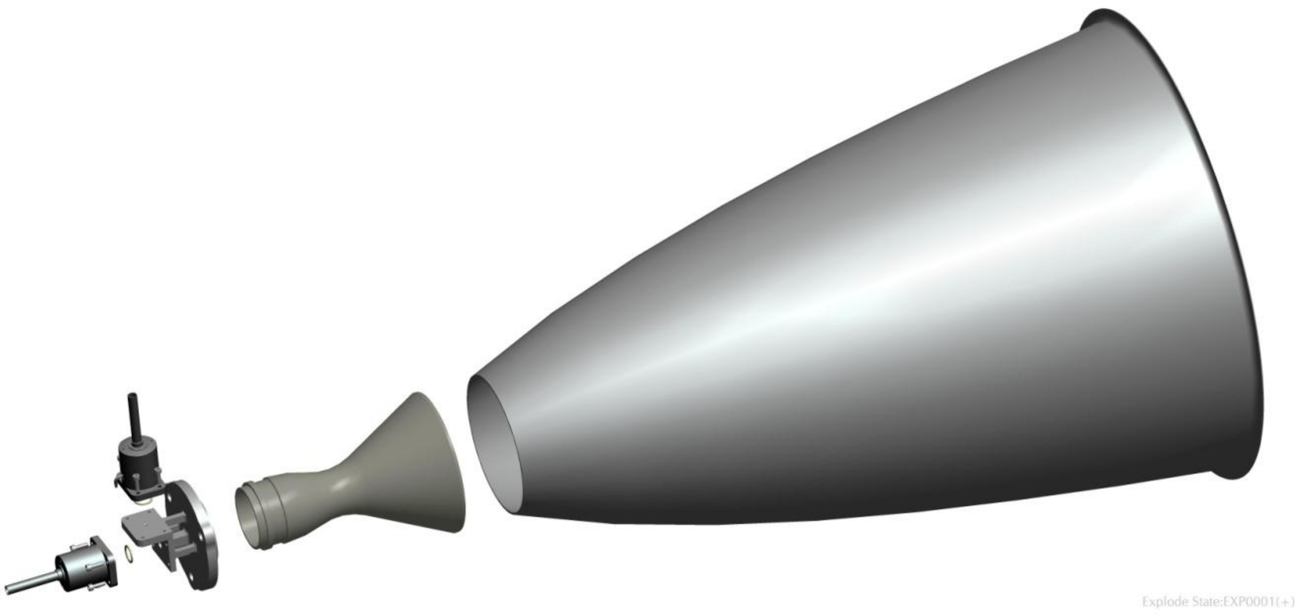
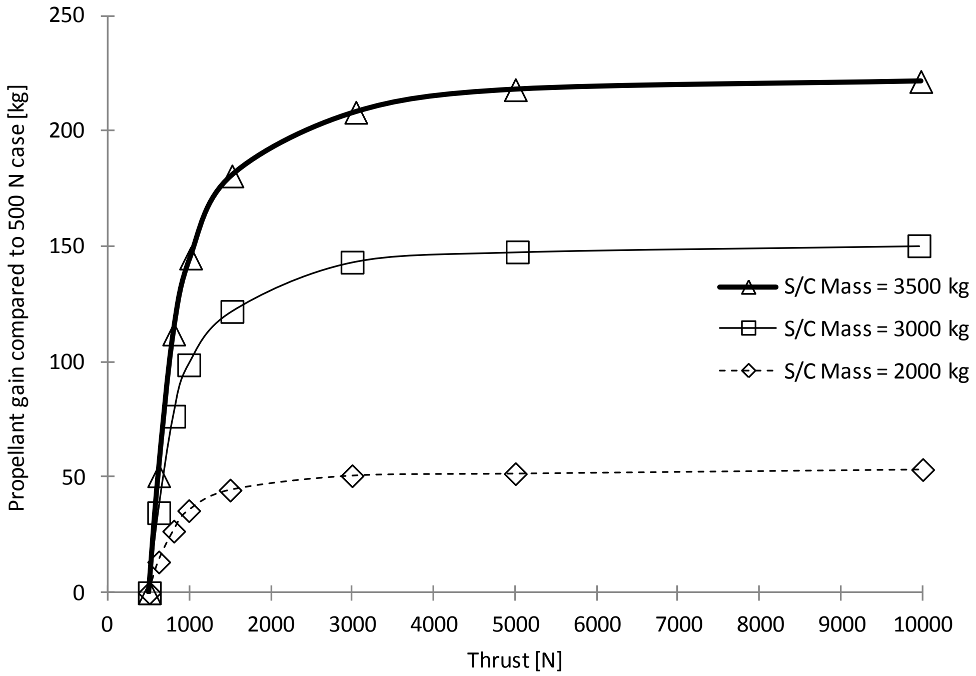


Figure 13: Component level view of the HTAE showing (left to right) valves, injector head assembly, combustion chamber, expansion nozzle.

Errata 23April 2013

A. The legend in Figure2 is incorrect. The corrected figure is :



B. The heading in the Materials section 1 should read 'High temperature noble metal (Pt alloy)'
C. References to the JAXA Planet-B mission in the Materials section 2 should read 'Planet-**C**'
D. The text in Figure 7 should read 'Increasing UID number increases RSS margin for wide thrust range operation'