QUALIFICATION TESTING OF A HIGH-PERFORMANCE 22N GREEN BIPROPELLANT ROCKET ENGINE USING HIGH-TEST PEROXIDE AND OCTANE

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ABSTRACT:

Although hydrogen peroxide-based monopropellant engines have a long history, the full capabilities of peroxide as a high-performance oxidizer in bipropellant engines remain underutilized in industry. In addition to obtaining flight heritage on a similar model, Benchmark Space Systems has completed qualification testing of the “Ocelot” 90% High-Test Peroxide (HTP) and Octane bipropellant engine. Using a packed bed catalyst and a radiative-cooled refractory chamber, Ocelot demonstrated 22N of thrust, 290s of Isp and an unlimited burn duration in bipropellant mode, while also supplying low minimum impulse bits as a catalytic monopropellant thruster when required. Combined with the unusually high impulse density and easy handling of its propellants, this makes ‘Ocelot’, and bipropellant peroxide in general, an attractive new frontier for in-space maneuverability and control.

1. INTRODUCTION

Hydrogen peroxide has a long history in aerospace as a monopropellant, but bipropellant peroxide engines are rarer, despite their high impulse density and efficient combustion. In introducing a series of bipropellant engines, Benchmark aimed to fill this market space.

The first revision of Ocelot, the 1.0 engine, was designed and tested in 2020-2022. After completing a proto-qualification campaign and meeting performance specifications, the engine successfully powered the Spaceflight Sherpa spacecraft.

Following the success of the original version, Benchmark produced an Ocelot 1.1, aimed to be the first fully qualified and high-rate engine design in the series. Qualification was also aimed to better understand the performance of the catalyst bed and downstream injection to inform the final, fully productized design, Ocelot 1.2.

2. QUALIFICATION OF THE 1.1 DESIGN

2.1. Test Article

An Ocelot 1.1 is pictured below and consists of a welded engine body. High-test peroxide is injected into a packed-bed catalyst. Fuel is then atomized and injected downstream. The thrust chamber is made of a coated high-temperature refractory metal.

Figure 1. Ocelot 1.1 Engine

The engine was qualified alongside valves and a pressure sensor, but all components were packaged separately. The configuration of those components, including tubing length and volume, was held as a constraint to be matched in flight configurations.

2.2. Facility and Capabilities

The Ocelot 1.1 qualification campaign was completed almost entirely using in-house resources.

Benchmark’s Vermont headquarters contains a full set of dynamic environment and thermal-vacuum test equipment and cleanroom, capable of qualifying hardware in vibration and thermal/vacuum to F9 RPUG levels.

Figure 2. BSS TVAC Equipment

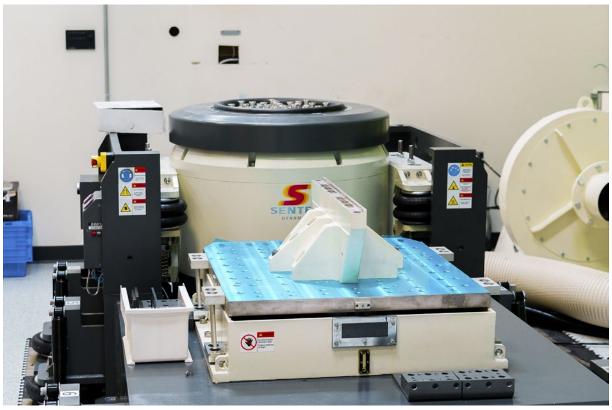

Figure 3. BSS Vibe Equipment

Figure 4. BSS Assembly Cleanroom.

Benchmark's CA facility furnished a hotfire test stand capable of multi-minute continuous burns. Chamber pressure was taken with an Omega PX459-050DWU5V high-rate transducer. Differential pressure measurements were used for massflow. Evolution Sensors K1X-WBWX-30G-EX-0.25-FGXX-40-MPCX thermocouples found chamber temperature readings.

2.3. Analytical Characterization

A reliable vacuum thrust measurement was not available in the scope of the test campaign. Because inviscid methods can overpredict thrust at this scale, computational fluid dynamics analysis was used to find a viscous solution.

Ocelot's nozzle is a 70% length bell contour. Several cases were considered with the using the k-ω SST turbulence model. Cases 5 and 6 approximated the inviscid solution.

Table 1. CFD Cases

Case ID	*Viscous Treatment*	*Inlet Boundary*	*External Wall Treatment*	*Geometry*	*ϵ*
1	k-ω SST	Pressure	Radiation	Parabolic	151
2	k-ω SST	Mass Flow	Radiation	Parabolic	151
3	k-ω SST	Pressure	Adiabatic	Parabolic	151
4	k-ω SST	Mass Flow	Adiabatic	Parabolic	151
5	Inviscid	Pressure	Radiation	Parabolic	151
6	Inviscid	Mass Flow	Radiation	Parabolic	151
7	k-ω SST	Pressure	Radiation	Cubic Fit	158
8	k-ω SST	Mass Flow	Radiation	Cubic Fit	158
9	k-ω SST	Pressure	Radiation	TIC	190
10	k-ω SST	Mass Flow	Radiation	TIC	190
11	k-ω SST	Pressure	Radiation	Parabolic	190
12	k-ω SST	Mass Flow	Radiation	Parabolic	190

Cases 5 and 6 came in close to the solution that a typical inviscid 1D solver would find. All other cases sat within 1% of one another across a wide range of nozzle geometry corrections and flow conditions.

Table 2. CFD Results

Case ID	*Thrust (N)*	*Cf*	*c* (m/sec)*	*Isp (sec)*
RPA	20.71	1.91	1534	299
0D Theory	20.46	1.89	1543	297
1	19.96	1.84	1605	302
2	20.90	1.84	1611	302
3	19.91	1.84	1606	301
4	20.92	1.84	1614	302
5	20.92	1.93	1599	315
6	21.72	1.93	1594	314
7	19.92	1.84	1603	301
8	21.10	1.84	1622	305
9	19.83	1.83	1602	299
10	20.82	1.83	1611	301
11	19.94	1.84	1602	301
12	20.93	1.84	1610	302

Benchmark aims to validate this analysis at the next available vacuum thrust testing opportunity.

2.4. Test Plan

Benchmark thrusters are qualified to a full set of environmental and operating conditions. The qualification campaign consisted of the below cases:

Table 3. Qual Loads

Test Condition	**Target Loads**
Acceptance Test	- 250 pulses, 150s burn. - Thrust, MR +-10% - Chamber Roughness BOL +- 10%
Random Vibration	20 GRMS, 2 mins ea axis
Sine Vibration	34 GRMS, 2 mins ea axis
Thermal Vacuum	- -34C to 71C at 1e-5 torr - Functional test with 30min Preheat to 250C
Comprehensive Performance Test	-Burn Time: 1450s min - # Pulses: 1700 min - Pcc range (biprop): 80-123psi - MR range: 4.3-7

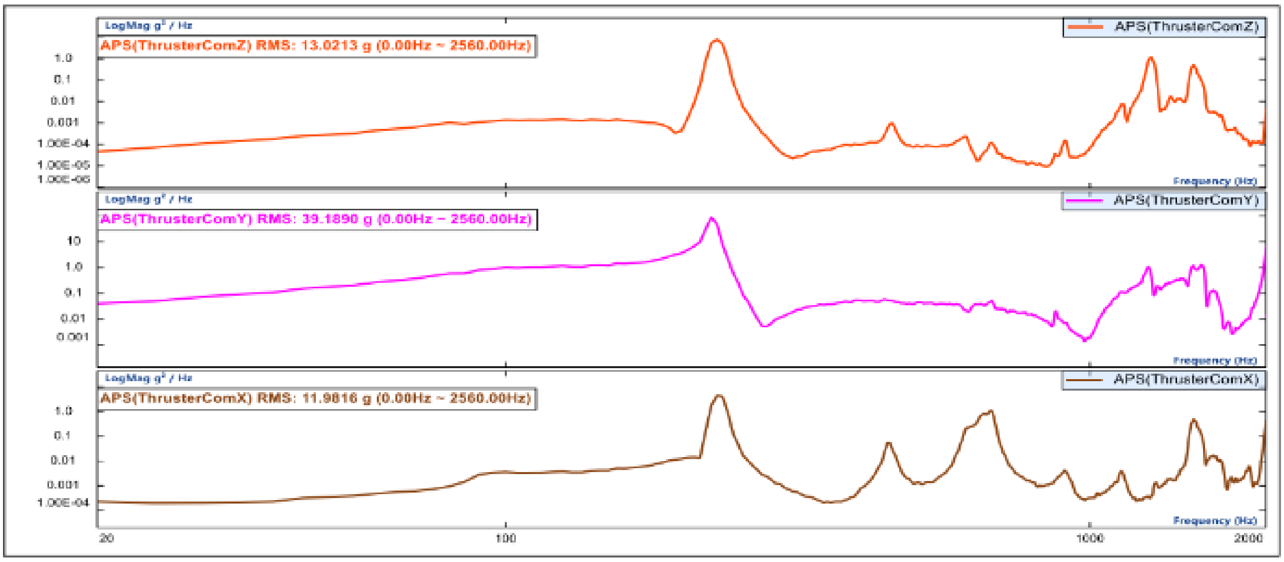

Figure 5. Sample Acceleration Data

2.5. Test Results – Environments

Ocelot was tested to vibration environments selected to bound anticipated environments at a two minute test duration. Each article survived, experienced no fundamental frequency shift above 5%, and passed subsequent performance testing.

Table 4. Qual Vibe Loads, Random

Frequency [Hz]	ASD Lateral [g2/Hz]	ASD Axial [g2/Hz]
20	0.026	0.026
100	0.9	0.65
205	0.9	
260	0.22	
400	0.22	0.65
500	0.16	
650		0.16
800		0.16
1000	0.16	
1050	0.4	
1150	0.4	
1200	0.24	
2000	0.1	0.026
GRMS	18.62	20.011

Likewise the test articles were passed through sine vibration testing to confirm capability in low-frequency transient vibration. All articles survived the levels below at a sweep rate of 2oct/min with no defects and without a fundamental frequency shift.

Table 5. Qual Vibe Loads, Sine

Frequency [Hz]	Accel [g]
5	1.27
6	1.83
10	5.11
11	6.18
50	7.5
100	10

Each engine successfully underwent thermal vacuum testing. During thermal vacuum cycles, heaters were cycled and engine electronics were verified.

Table 6. Qual Loads, TVAC

Test Condition	Value
Pressure	1e-5 [Torr]
Temp Range	-34 – 71 [C]
Dwell Time	>4 [hrs]
# Cycles	8 (final 6 at 1 atm)

2.6. Test Results – Performance Across Inlet Conditions

Ocelot 1.1 displayed stable performance in a wide variety of operating conditions. An example of a steady-state burn is below.

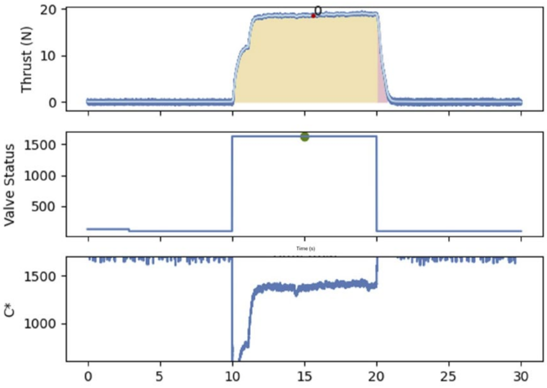

Figure 6. Sample Burn Data

To characterize performance across inlet conditions, thruster performance in both steady-state and pulsed operation was demonstrated in a variety of different inlet conditions. (See Pc-MR chart).

Due to the very high mixture ratio (typically 6:1), chamber pressure tended to be almost entirely determined by ox mass flow. Meanwhile, mixture ratio (and thus, combustion efficiency) was driven almost entirely by small variations in fuel mass flow. This relative insensitivity reduced coupled behaviour between engine inlet flows and expanded the feasible range of mixture ratios.

During this testing, c* came in consistently below expectations. The resolution of this issue is discussed in Part 3 below.

2.7. Test Results – Pulsed Performance

Ocelot's pulsed performance was characterized across a variety of duty cycles. Bipropellant ignition began to be marginal around 300-400ms pulses, leading to an according increase in c* variability.

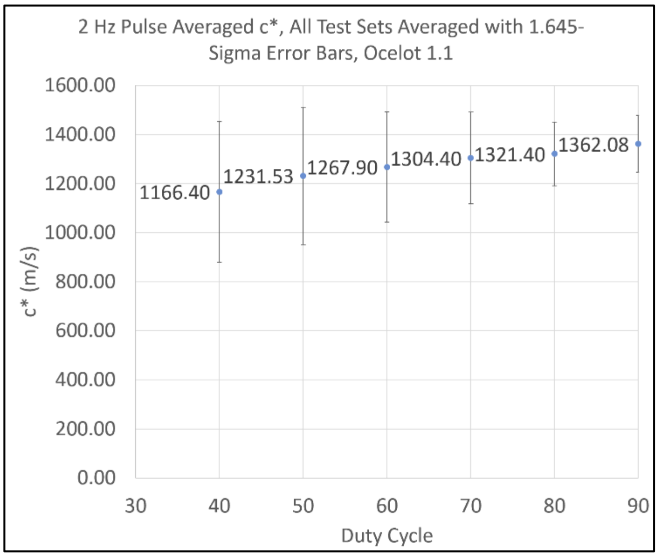

Figure 8. c Data*

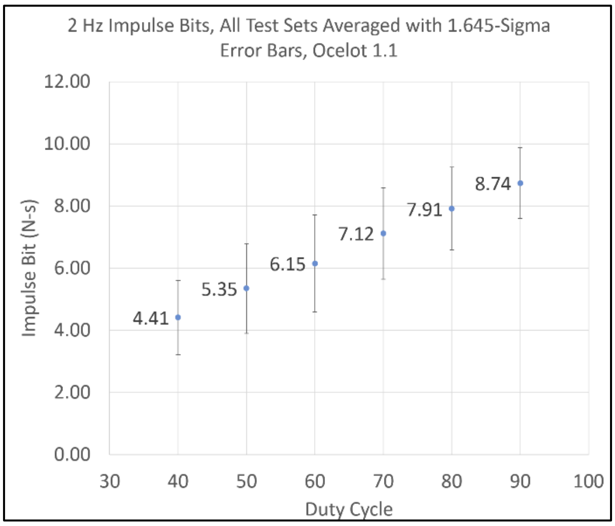

Figure 7. Impulse Bit Data

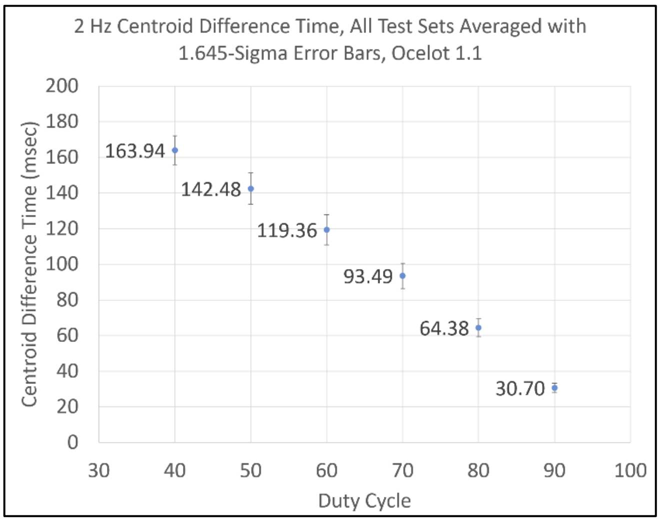

Figure 9. Centroid Diff. Time Data

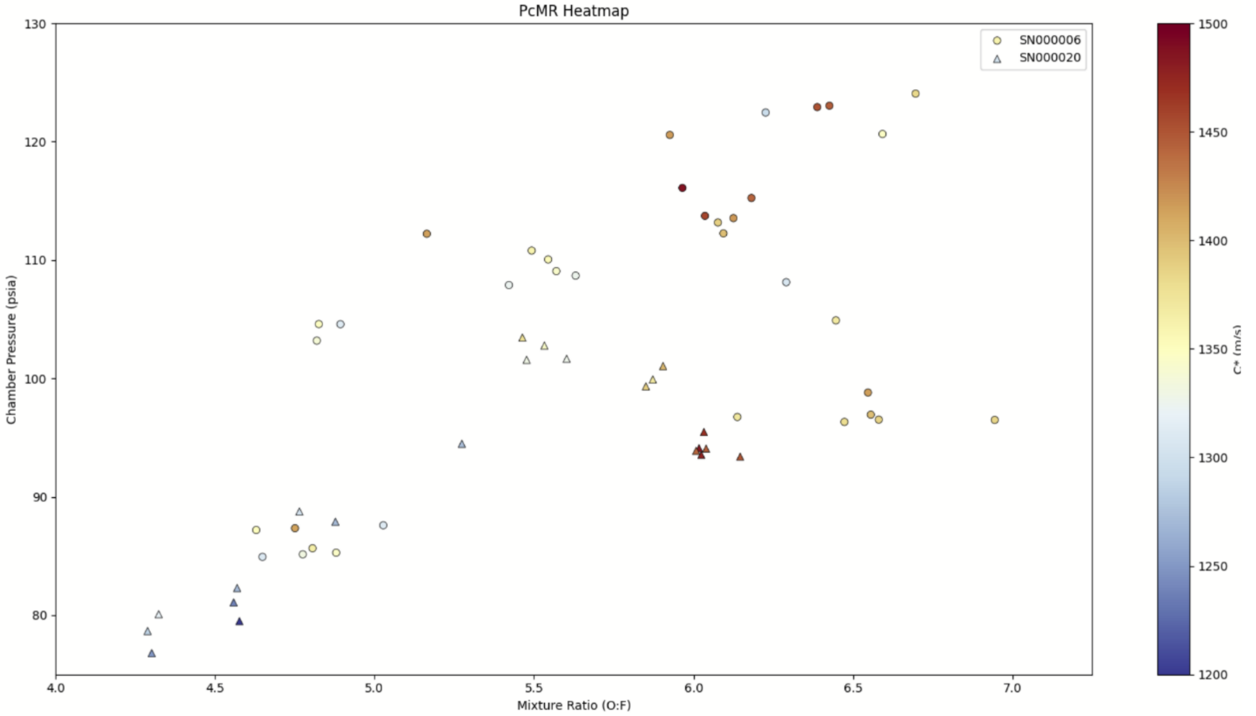

Figure 10. PcMR Heat Map

2.8. Test Results – Cold Starts

The thruster was tested in several cold start conditions to better understand cold start behaviour.

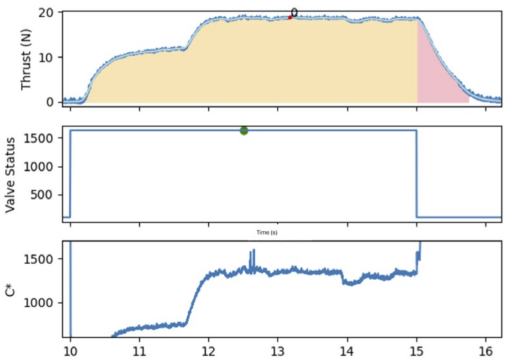

Figure 11. Sample Cold Start Thrust Curve

Ocelot was shown to be capable of up to twelve cold starts. However, over this process, damage to the catalyst was observed, leading to reduced flowrates and combustion efficiency over time. This could be improved in the future by continuing to refine the catalyst chemistry to increase robustness to thermal cycling-based failure modes.

2.9. Test Results – Propellant Inlet Temperature

A variety of propellant inlet temperatures were tested on the fuel side and found to have no indication of impact to ignition or combustion stability. Differences in efficiency were well within data variability.

Propellant inlet temperature testing with the hydrogen peroxide propellant is a target future test.

2.10. Test Results – Hard Start Condition

Unlike other thruster designs, the post-injection of fuel and dynamics design of the internal passages meant that Ocelot 1.1 was not especially sensitive to hard-starting because of valve or command dynamics. However, qualification testing found a zone of increased hard-start risk when operating in mixture ratios below 4.8, likely due to buildup of un-combusted fuel. Because this is well below the engine's nominal operating point, this failure mode was characterized but did not need to be resolved.

The high level of robustness required for catalyst retention meant that some hard-starts were actually survivable. Below is an example thrust curve with a significant pressure exceedance on startup that continued a nominal, albeit choppy, burn thereafter.

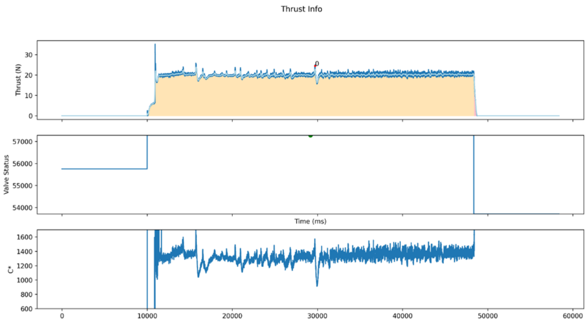

Figure 12. Sample Hard Start Thrust Curve

Similarly, the qualification campaign was able to identify the location of instability modes on both propellants. Because of the strong impact of oxidizer flow rate on chamber pressure, Ocelot depicted the unusual behaviour of uncoupled chugging, with cyclical disturbances on one propellant leaving the other one unaffected.

Inducing instability required either operating at extremely off-nominal injection points beyond even the margined qualification limits, so these modes were identified as not an operational concern.

2.11. Post-Qualification Development Testing

After competition of formal qualification, Ocelot 1.1 was taken through a variety of development tests to further anchor performance and fact-find before the development of the next version could begin.

A highly thermally instrumented Ocelot was fired to a variety of steady-state conditions, including in a vacuum chamber. Besides validating the basic performance of the engine in a vacuum, this testing helped ground thermal modelling of the engine that would be crucial for later design.

Ocelot engines were pushed to the operating limits. Basic viability tests with 80% and 98% peroxide were conducted, although 98% peroxide testing had to be conducted cautiously because high temperatures would rapidly damage the thruster.

Seven used Ocelot engines were subjected to a complete teardown to help understand the impact of long lifetimes on the engine. Key shock and temperature sensitive internal retention components were identified and highlighted for future design modification. Used catalysts were subjected to chemical analysis to better understand their behaviour. There were many interesting results here – high detections of sodium salts in catalyst beds, for instance, were identified as residue from various sodium-based catalyst stabilizers. For the life-limiting engines, specific modes of catalyst damage were identified, informing lifetime on future thrusters.

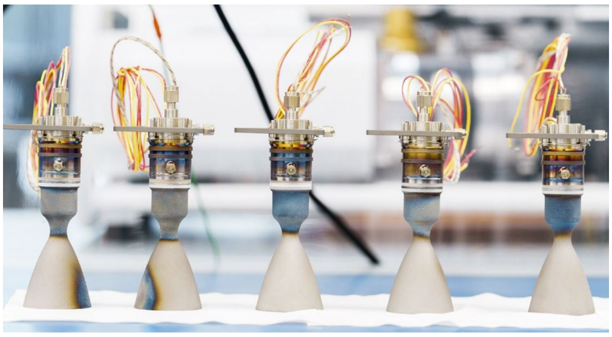

Figure 13. Ocelot 1.1 Thrusters After Test

3. UPGRADE TO 1.2

The 1.1 qualification campaign was successful in its full characterization of the thruster. It also found several places where the thruster design could be improved in advance of achieving full-rate production.

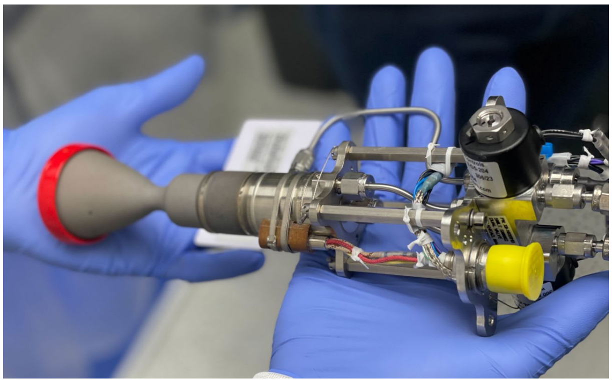

Figure 14. Ocelot 1.2 Development Article

3.1. Combustion Efficiency

The first major focus area was in combustion efficiency. Despite well-demonstrated atomization from the injector, the thrust chamber on the Ocelot 1.1 demonstrated little margin on ignition capability, making it vulnerable to small perturbations in operating conditions.

Benchmark followed several paths to resolve this issue this, including a substantial investigation into small changes in apparently very similar catalyst materials. Ultimately, Benchmark determined that the core of the issue was insufficient mixing inside the chamber, due in part to chamber geometry and in part to unexpected channelling behaviour.

To solve this issue, Benchmark substantially changed chamber internal geometry to encourage mixing, decrease channelling, and broadly increase the chamber L*.

This approach was first tested on a series of stainless steel test articles. After rapidly iterating through four sets of hardware, Benchmark was able to identify an effective chamber geometry, and proceeded to full-scale operation with a modified version of the original chamber.

The new configuration demonstrated substantially improved performance, operating reliably at nearly 99% of the theoretical peak c* efficiency.

The difference in temperature is clearly visible in the images below.

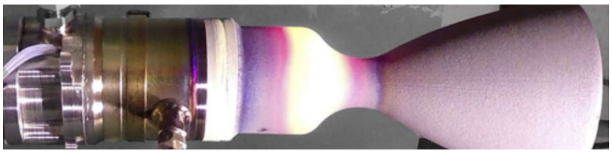

Figure 15. Ocelot 1.1 Bipropellant Operation

Figure 15. Ocelot 1.2 Bipropellant Operation

In addition to offering notably higher performance, the increased combustion efficiency made it possible to reliably ignite Ocelot with multiple other propellants. Although there is nothing theoretical preventing Ocelot from burning nearly any hydrocarbon as a fuel, in practice the vaporization enthalpy and heat capacity of different hydrocarbons make them variably difficult to ignite. Ocelot 1.2 was successfully ignited with IPA in addition to Octane, and a variety of other fuels, including RP-1 and Butane, are planned for future testing.

3.2. Pulse Performance

Another key opportunity for improvement of the Ocelot 1.1 design was pulsed performance. While the 1.1 was capable of long burns, it had a relatively slow pulsed performance.

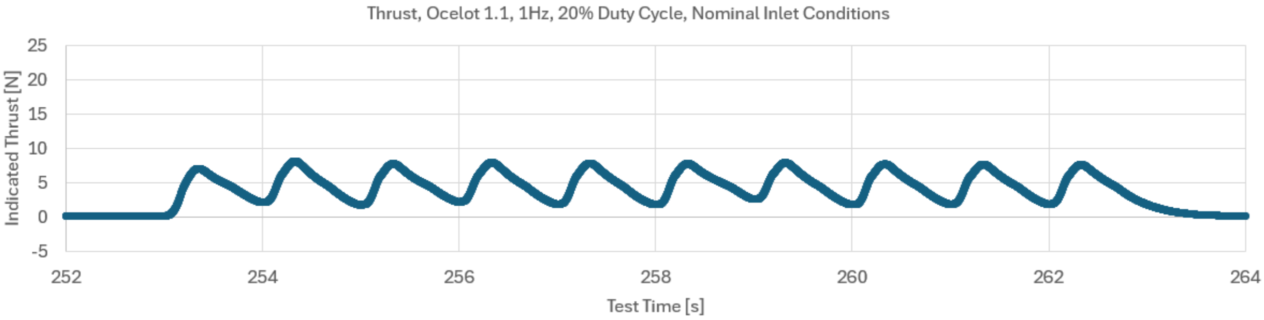

Figure 16. Ocelot 1.1 Pulse Data

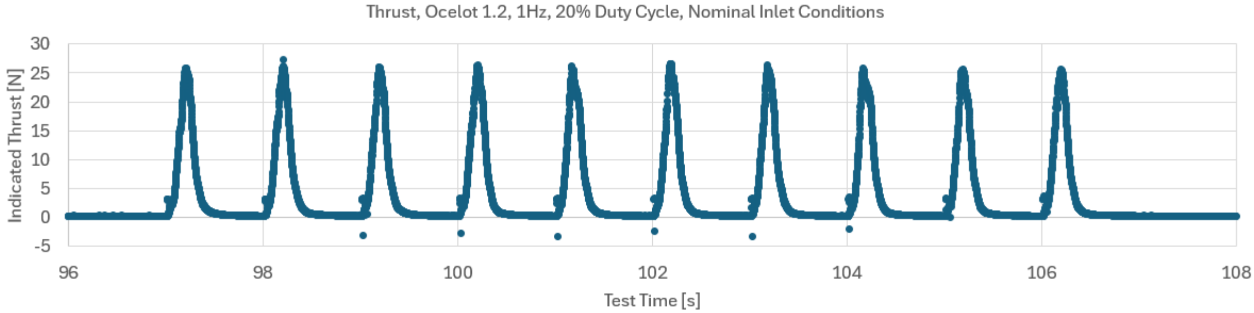

Figure 17. Ocelot 1.2 Pulse Data

This was in large part due to the large “dribble volume”, the volume upstream of the chamber that filled with propellant when valves were actuated. A key design goal for the Ocelot 1.2 was the reduction of the dribble volume.

Key changes included:

- The internal geometry was fully redesigned to reduce volumes.
- Press-fit plugs allowed more complex and nimble internal geometry that could be drilled smaller.
- Improved internal filtration made smaller internal passages safe to use.

Optimization of the upstream oxidizer spreader manifold kept pressure drops manageable during this process.

However, the key element for reducing dribble volumes and thus improving pulsed performance was the productization of the valves into a single manifold assembly. This both improved integration by inherently controlling valve performance and reduced dribble volume by allowing a compact packaging of valves with the thruster.

Finally, the valves themselves were changed. A new design with a stronger coil and smaller orifice provided faster retraction times and snappier behaviour.

The combination of all of these factors substantially improved pulsed performance. While Ocelot 1.1 was unable to reliably enter bipropellant combustion below 40% of nominal operation, Ocelot 1.2 comes up to full chamber pressure even at 20% duty cycle and demonstrates rise times below 200ms.

3.3. Fuel Pulsing Mode

Following customer demand, Benchmark spent time qualifying Ocelot 1.2 to operate in a “fuel pulsing” mode in which the oxidizer valve was held open while pulsing the fuel valve, causing Isp and thrust to pulse in between monopropellant and bipropellant values. This was found to be a robust control mechanism.

3.4. Catalyst Fine Migration

A classic problem with catalysed thrusters is retention of particulate catalyst. Catalyst fines leaving the bed can lead to FOD contamination of other systems or, in the case of upstream catalyst loss, even clog injectors.

Ocelot 1.1 was qualified to vibe environments in certain configurations, but to continue to improve the survivability in harsher environments, Ocelot 1.2’s filtering system was redesigned. One key lesson learned was that retention of filters themselves became more limiting than the filter’s micron ratings, as the primary catalyst migration vector became the spaces around the edges of filters or even the perpendicular path along their face. Another was that particulate catalyst exhibits a clumping behaviour that makes traditional FOD rules (such as the NASA Three-Ball Method) not necessarily conservative, because several very small fines can cause clogging when clumped even when none of them would be able to do so individually. Ultimately these issues were resolved in development testing.

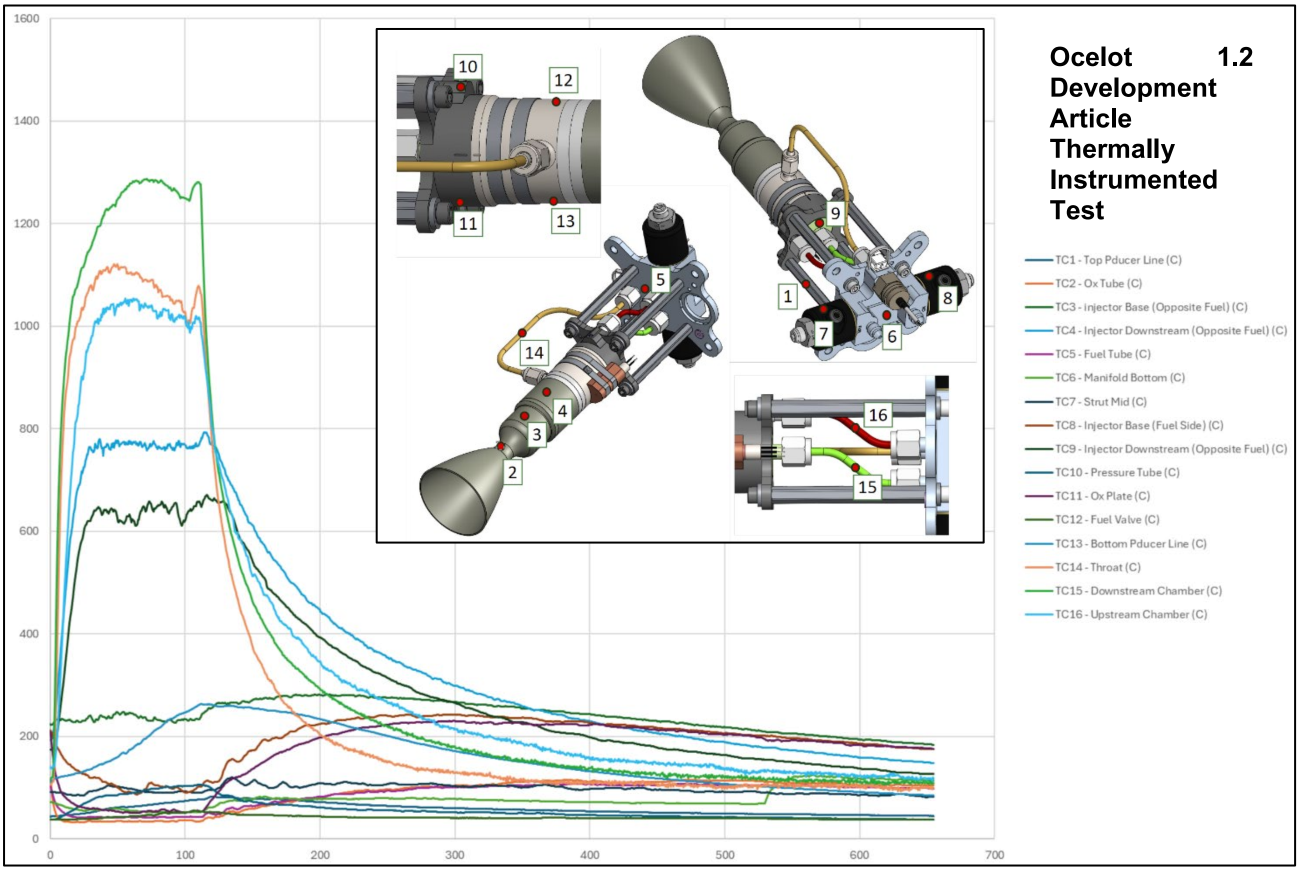

Figure 18. Ocelot 1.2 Thermal Data

3.5. Higher Temperatures

Higher performance efficiency led to much higher engine temperatures than the 1.1, pushing the hottest sections of the throat close to 1400C. This required a number of adjustments.

The engine was placed on titanium standoffs with a low thermal conductivity to help isolate valves and sensitive components from the rest of the package. Thermally induced stresses and strains in the tubing between the valve and the injector body were analysed and tested to confirm thruster lifetime despite this change.

Parts of the internal thruster body had to have their material changed to better protect them against corrosion. Although the Ocelot 1.1 was largely made out of austenitic stainless steel, traditional

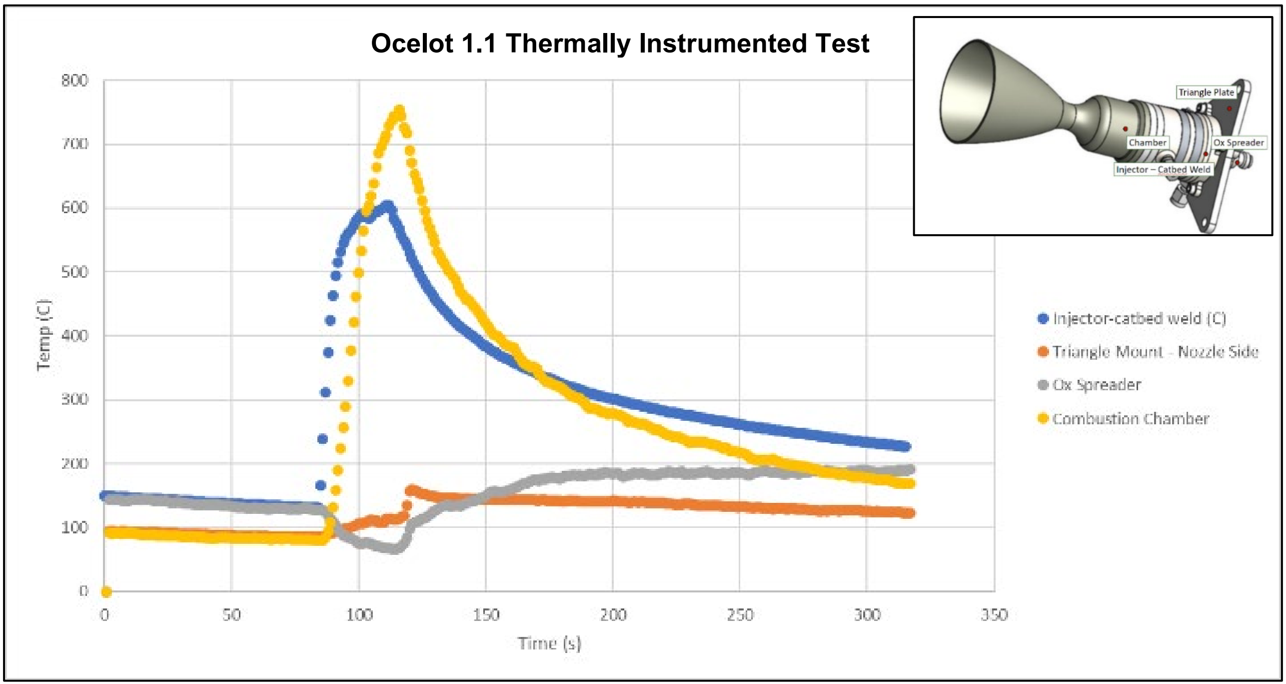

Figure 19. Ocelot 1.1 Thermal Data

welded grades of stainless steel suffered temperature sensitive high rates of corrosion in the highly water-filled chamber environment. This behaviour was further encouraged by the cyclic nature of thruster operations – repeated thermal cycles appeared to cause thermal expansion mismatch between the exterior chromium layer and the stainless bulk material, which in turn led to more rapid corrosion on the steel segment.

Although there was some theoretical uncertainty, final testing showed that the current chamber material and oxidization coating were able to survive the extremely high-temperature oxidizing environment with no observed impact to engine performance or structural margins.

3.6. Integrated Assembly

Integrating the entire assembly into a thruster product improved the thruster operations in a number of other ways.

- Upstream filtering built in above the valve, helping reduce instances of FOD ingestion into the thruster body.
- Built-in trim orifices, allowing the engine to be configured to drag scenarios where active drag control might be warranted.
- Fully productized valves and connector, creating a cleaner customer interface with a single electrical connector and built-in heating control for the valves and electrical system.

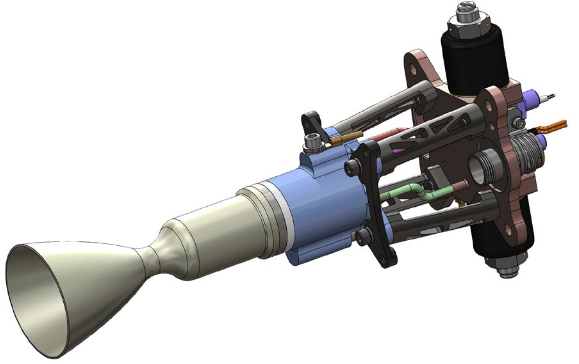

Figure 20. Ocelot 1.2 Final CAD

3.7. New Performance

Ocelot 1.2 is presently proceeding into qualification testing. Initial portions of qualification testing have assessed broad improvements in performance.

Table 7. Performance Comparison, 1.1 to 1.2

Parameter	**Ocelot 1.1**	**Ocelot 1.2**
Steady-State Thrust [N]	18.2	22
c* [m/s]	1410	1546
Rise Time [s]	1512	< 200
90% Duty Cycle Impulse Bit, Monoprop [Ns]	<12	< 9
90% Duty Cycle Impulse Bit, Biprop [Ns]	< 20.5	< 18.5
90% Duty Cycle c*, Biprop [m/s]	1392	1550
90% Duty Cycle Centroid Difference Time [ms]	< 70	< 65
20% Duty Cycle Impulse Bit, Monoprop [Ns]	< 3.5	< 1.8
20% Duty Cycle Impulse Bit, Biprop [Ns]	< 5	< 4
20% Duty Cycle Centroid Difference Time [ms]	< 170	<110

An alternate approach is to compare the performance of Ocelot 1.2 against an industry-standard hydrazine thruster of the same class, like the MOOG 5 LBF thruster.

Table 8. Performance Comparison, Ocelot 1.2 to MOOG 5 LBF Thruster

Parameter	**MOOG 5 LBF [1]**	**Ocelot 1.2**
Propellant	MMH/MON	90% H2O2/ Octane
Steady Thrust [N]	22	22
Nominal MR	1.65	5.92
Mass [kg]	0.91	1.1
Specific Impulse [Ns/kg]	2786	2844
Impulse Density [Ns/L]	3235	3454

Data for the MOOG 5 LBF thruster is taken from Ref. 1 or extrapolated from Ref. 1 data.

Ocelot's current performance has still not reached its theoretical maximum. The engine is currently operated near the 4:1 volume ratio for thermal and propellant packaging reasons. Designing for even higher mixture ratios – and higher concentrations of peroxide – can continue to increase specific impulse to a theoretical maximum of 317s, above hydrazine thrusters like the MOOG DST-11H.

3.8. Future Work

The first priority for future Ocelot work will be to continue to increase performance. Design for even higher temperature operation will make it possible to run the engine on 98% peroxide instead of 90% peroxide, which supplies both a higher Isp and is easier to store for long periods. Making this possible will likely require looking into different chamber manufacturing and coating processes. Benchmark is currently engaged in active research and hopes to qualify an alternative to the very expensive Iridium-Rhenium chambers commonly used in industry.

The second is to further expand capabilities. Thanks to Benchmark's SmartAIM GNC system, Ocelot ships ready for a variety of control-centric use cases. Although it is currently very capable of pulsed performance for tight control, direct realization of throttling capabilities will push it even further and expand its operational utility.

4. CONCLUSION

Benchmark’s Ocelot engine has been operating in space for over a year and has substantial additional flight heritage on the horizon in both reaction control and manoeuvring applications. As development in bipropellant peroxide architectures in Ocelot’s range proliferate through the industry, this research presents lessons for new engine development programs by to outlining unique design and manufacturing pitfalls as well as performance advantages of bipropellant peroxide.

5. AWKNOWLEDGEMENTS

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6. REFERENCES

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