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QUALIFICATION AND PRODUCTIZATION FOR MANUFACTURING OF THE OCELOT ROCKET ENGINE

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As the space industry grows quickly and green propellants enjoy growing interest, the key question of research is no longer basic viability but productization. The most valuable engine is one that is qualified and available as close to "off the shelf" as possible. But publications on the process of taking an engine from first demonstrations to true product status are rare. This paper describes the process of transitioning Benchmark Space Systems' 22N Ocelot engine – first flown as the 1.0 product version in 2022 – into a high-volume, well-characterized product, including details on the qualification program for the 1.2 version, learnings from rate production, and a deep dive into a particular production reliability issue. In doing so, it hopes to shed light on not only spacecraft thruster production but on the productization of space technology in general.

Keywords: low-volume manufacturing, space qualification, propulsion

1. Introduction

Benchmark Space Systems has been developing a 22N bipropellant peroxide thruster since 2020. It was successfully flown first in 2022, and powered Spaceflight's Sherpa spacecraft, The Exploration Company's Mission Possible, and now Varda Space Industries' first in-house spacecraft. Unlike traditional spacecraft engines, which typically use very toxic hypergolic propellants like hydrazine and nitrogen tetroxide, Ocelot uses hydrogen peroxide and octane, enabling faster iteration and much simpler manufacturing processes [1]. Peroxide based engines have a long history [2], but until recently have had few commercial successes.

Very low-volume markets like that of rocket propulsion present unusual challenges, especially designing engine qualification so that it accommodates minimum non-recurring engineering after qual conclusion and minimizing lead time for individual jobs. This paper describes an effort to achieve both.

2. Qualification of the 1.2 design

Having replaced the 1.1 version of the thruster, the 1.2 was first qualified in a formal program per a tailored version of SMC-S-016 [3].

2.1. Test article

The Ocelot 1.2 engine assembly (*Figure 1*) consists of a valve and sensor manifold mounted to a thruster 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.

Unlike the Ocelot 1.1 design, the 1.2 thruster assembly is qualified as a unit, including valves, sensors, harnessing and tuning orifices.

Figure 1: Ocelot 1.2G

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Table 1: Test conditions

Test condition	Target loads
Acceptance	- Cv and pressure proof. - Through and external leakage. - Electrical functional. - 100s of hotfire, including monoprop, biprop, pulsed and steady state operation.
Vibration	- Loads bounding on GEVS and F9 RPUG conditions. (See below)
Thermal vacuum	- Temperature bounds bounding on GEVS and F9 RPUG (See below). Functional tests throughout.
Hotfire	- Complete lifetime in total time, time at temperature, pressure cycles and temperature cycles. - Performance across PcMR points (see below) in steady and pulsed modes. - Unit life variation tests. - Minimum impulse bits down to 2.5% duty cycle, repeated to statistical significance. - Post-hotfire inspection, teardown and weld NDT.

2.2. Facility and capabilities

The Ocelot 1.2 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 NASA GEVS and F9 RPUG levels. Given the commercial ubiquity of SpaceX, SpaceX launch vehicle loads are a key design parameter.

All hotfire was conducted at BSS's facility in Pleasanton, CA. Benchmark's test stand is capable of long and short duration burns with high rate telemetry of pressure, temperature, and mass flow.

2.3. Test plan

Benchmark thrusters are qualified to a full set of environmental and operating conditions (*Table 1*). The qualification campaign consisted of the below cases.

2.4. Test results – Environments

Ocelot was tested to vibration environments selected to bound anticipated customer environments at a two-minute test duration (*Figure 2*). Each article survived, experienced no fundamental frequency shift above 5%, and passed subsequent performance testing.

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 2 oct/min with no defects and without a fundamental frequency shift.

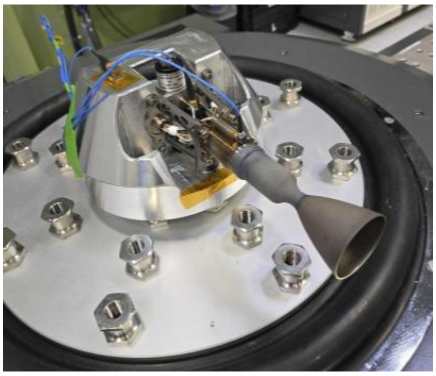

Figure 2: Vibration fixture

Each engine successfully underwent thermal vacuum testing. During thermal vacuum cycles, heaters were cycled and engine electronics were verified. These environments are bounding on a wide variety of customers, minimizing non-recurring engineering and maximizing the likelihood that the engine will be able to accommodate any given mission. They are also designed to be bounding on various production contingencies to improve production yield.

2.5. Test results – Performance across inlet conditions

One advantage of the bipropellant full-flow catalyst bed architecture is an unusually broad operating range. All BSS thrusters are qualified to a 5% operational and 10% qualification box – in excess of SMC requirements – to maximize customer flexibility and mission assurance.

To ensure box compliance, the qual units underwent both thermal steady state characterization and a sweep of different pulse trains at a variety of points across the operating box (*Figure 3*).

2.6. Test results – Burn-to-burn variation

Consistent burn to burn performance across the life of the article is key to dependable operation for the customer. To ensure this, BSS carried out identical steady and pulsed profiles at various points during the qualification campaign, matching inlet and heat conditions, in order to demonstrate thruster performance variation. *Figure 4* shows profiles at the beginning and end of the unit's life in orange and blue.

2.7. Test results – Minimum impulse bit

Ocelot's full-flow catalyst bed and non-hypergolic propellants make it slower to ignite than some competing hypergolic thrusters. Considerable flow optimization was done to improve these properties. During qualification, the engine reached minimum impulse bits below 0.06Ns, a substantial improvement compared to the 1.1's rated impulse bit of about 1Ns, and close to that of thrusts with

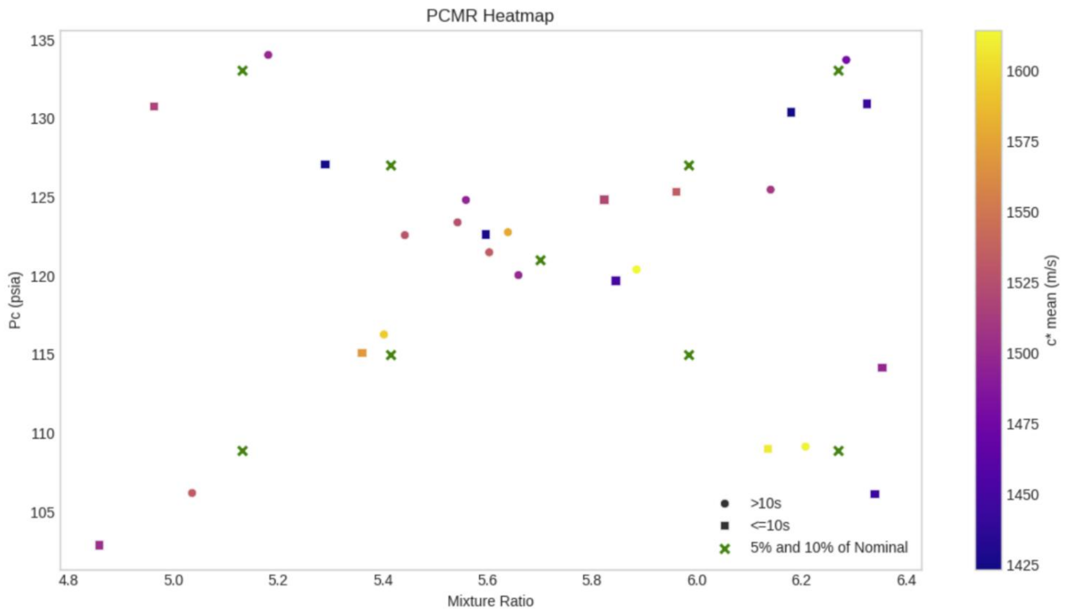

Figure 3: Thruster PcMR operating points

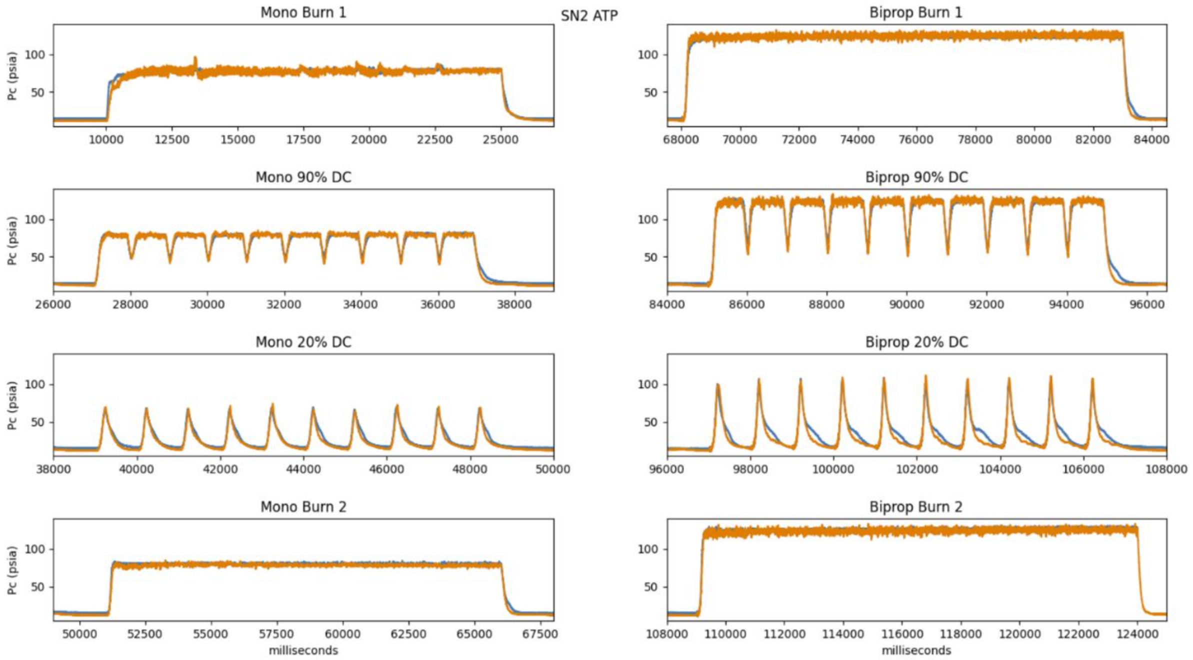

Figure 4: Repeatability, compared at the beginning and end of the engine life

substantially faster fundamental propellant properties such as the L3 Harris MR-106 [4].

2.8. Test results – Duration operation

Unlike 1.1, the 1.2 Ocelot thruster is rated to continuous steady state operation for the entire unit life. Both qualification units were subjected to substantial long-duration burns to demonstrate this capability, with SN7 in particular operating for 500s of continuous burn and 500s of high-duty cycle pulsed burn. This is longer than key alternatives, including the L3 Harris AJ10-220 [5] and Rubicon 22N LT [6].

2.9. Test results – Off-pulsing

A common customer use case is “off-pulsing” operation – firing the thruster in a near-continuous fashion but occasionally shutting it off to throttle. Since this mode repeatedly incurs start and fall transients during operation, the equivalent Isp is lower than it would be during steady operation. Due to its prevalence, BSS worked to demonstrate it in actual operation. This operating mode was new for the 1.2 version.

2.10. Test results – Total unit life

SN2 was subject to margin on total pulse count, at the cost of not operating for long continuous periods at full power. SN7 was subject to total life, at the cost of a reduced pulse count. Both thrusters were run to 2x qualified unit life. With the successful conclusion of both runs, the qualification was deemed complete.

3. Further testing

While BSS has a formal set of requirements for thruster qualification, mission assurance is a priority and BSS is consistently focused on further characterizing thruster behavior to best inform customers. This is absolutely central – additional testing both anticipates customer needs, which lowers non-recurring engineering, and, by finding the limits of the assembly, allows further production optimization and the acceptance of deviances in production. Some examples of selected additional testing are listed below.

3.1. Voltage input range

One customer need that became apparent during the productization process was for the thruster to be able to accept a wide range of inlet voltages. Thus, Ocelot was tested to ensure that it would function correctly at any inlet voltage between 24 and 33.6 V, even if that supply voltage had to change unexpectedly during operation and even if on-bus closed loop control was not available.

Valve resistance and thermal behavior was comprehensively characterized across the range of possible input voltages, and energization tests were conducted across the spectrum to characterize performance impacts and survivability of all electrical hardware.

3.2. Heater survival testing

Especially crucial was the survival of the unit's resistive heater. To ensure that no electronic or structural component would run into trouble in a variety of heater overpower scenarios, a representative thruster was taken through representative heater transients at low and high voltages in limit cold, limit hot and room temperatures in a hard vacuum and was stressed until electrical failure. With this data, BSS can provide customers with a fully margined limit temperature on the catalyst bed telemetry, regardless of their bus electrical configuration.

3.3. Lower peroxide concentration

Peroxide decomposes slowly during storage. In off-nominal temperature or operational cases it might decompose faster, so one contingency scenario that our customers show interest in is the engine's capability to operate at progressively lower peroxide concentrations than the typically recommended condition. To provide margin and inform performance estimates, BSS operated the thruster at mass-wise peroxide concentrations as low as 84% and pulled directly correlated performance laws against concentration in a variety of cases.

3.4. Thrust axis testing

Unit to unit accuracy of the thrust axis against the mounting location is a key priority of many customers. To help support better insight into the as-built behavior of engines, BSS carried out CMM measurement operations on several production engines, comparing the alignment of the vector defined by the centroids of the nozzle throat and chamber exit with the plane of the mounting flange. This analysis found that the as-built configuration, as designed, was well within 1 degree with three sigma accuracy.

3.5. Additional vibration testing

Although the formal qualification program followed two Ocelot thrusters through a qual-bounding vibration profile, a range of thrusters was extensively operated in a variety of off-nominal vibration conditions to qualify various other issues.

For example, catalyst beds in industry literature can have a reputation for vibration sensitivity. To ensure good performance, the thruster was run for eight qual lifetimes, with functional tests throughout and breakdowns to inspect for catalyst FOD throughout the process. The unit demonstrated passing functional tests after this.

Six more units were subjected to qualification-level vibration. These carried out a variety of objectives, including:

- Demonstration of customer-specific load conditions.
- Identification of soft good lifetimes.
- Demonstration of a variety of other vibration orientations besides the typical.

All vibrated thrusters passed functional tests afterwards.

3.6. Recovery options

Catalyst bed thrusters can be sensitive to fouling, poisoning, or even simple waterlogging, which can reduce catalyst performance. Due to the path dependent nature of catalyst bed operations, operating with a damaged catalyst bed can sometimes cause further damage.

Although BSS has developed the procedures for proper handling of a catalyst bed to ensure good life, things sometimes go wrong. To help support recovery of a damaged or misused catalyst bed, BSS developed a procedure for non-hotfire emergency drying and reconditioning of a used thruster and demonstrated it on multiple waterlogged units, showing a return to production-quality performance specifications.

3.7. Weld post-qualification

All welds on the thruster were independently qualified per BSS internal standards, including metallographic inspection, multiple qual units, and structural testing. The qualification thrusters themselves were subjected to NDT after the completion of qualification life as well. In addition, further testing was conducted to demonstrate compliance with customer cyclic loading requests. In particular, because the welded feedlines encounter cyclic loading during thermal cycles on the unit, representative samples were subjected to bounding loading cycles and proved total unit life.

4. Productization

4.1. Catalyst bed packing

Unit-to-unit variability is enormously important when packing and installing catalyst beds. Throughout the high-rate production process, BSS identified and eliminated several key sources of variation. Most notable among them was humidity. Specifying bed loading using a mass led to a small but meaningful error as catalyst accumulated trace moisture from the atmosphere during the packing process. Due to the micropore construction of the catalyst, this turned out to have a meaningful impact on results even despite the environmental control of the packing area. Catalyst is now packed on a volume basis, substantially reducing variability in a way visible in hotfire operations.

4.2. Catalyst startup

Through the acceptance of dozens of units, BSS had the opportunity to make substantial optimizations to the pre-conditioning and early operation of the catalyst bed. After considerable experimentation across flight-like units as well as development articles, a particular series of runs ramping bed loading and running an off-nominal preheat configuration early in operation was found to substantially increase catalyst performance and variability across the shipset. This sequence helps burn off residual, condition the catalyst substrate, reduce catalyst susceptibility to poisoning or agglomeration, and improve life.

4.3. OTW yield increase

To increase reliability and reduce leaks, all fluid joints on the Ocelot 1.2 were welded. In the case of the tubing in between the valve manifold and the thruster body, these needed to be orbitally welded. Occasional issues cropped up in the welding process for these thin tubes due to the existing flow constrictions downstream, which made maintenance of sufficient but not overwhelming purge flow challenging. BSS developed a custom orbital welding setup that was able to maximize yield on this process over nearly a dozen iterations and hundreds of welding operations.

4.4. Production sequence improvement

One major design goal of the 1.2 iteration was to reduce the production sequence by allowing all external welds to be co-scheduled. This reduces work-in-progress unit count and increases utilization of resource by reducing station-shifting, especially key aspects in flexible manufacturing [7]. With the welds redesigned and batched, and various acceptance steps automated, a thruster can go from inventory arrival to completed acceptance test in less than three weeks, and BSS's production facility is capable, at maximum throughput, of over one thruster a day.

4.5. Feedline drag optimization

One key element of the productization process was the addition of tuneable upstream orifices. Using these, BSS can be responsive to the specific needs of a customer feed system, including tailoring units to individual customer serial numbers and targeting defined inlet pressures.

A test series was carried out that demonstrated <1% accuracy in between estimated and realized full system drag for each unit.

4.6. Valve seat variation control

As production volume continued to scale, BSS identified variation in the sealing efficiency of valve seats under vibration conditions. After multiple vibration tests, this was eventually traced to microscopic scarring on the valve soft goods from large manufacturing lots as well as some additional FOD sources. BSS was able to update acceptance criteria and verify good valve performance thereafter.

4.7. Harnessing improvements

After passing full qualification vibration testing, the harnessing set on the thruster was found to be susceptible to low-frequency behavior during transport handling in cross-country shipping that had not been covered by the previous vibration tests. A harnessing design improvement resolved this issue, and bounding vibration tests confirmed the solution.

4.8. Purge operations

Dryness of the thruster interior is of course of extreme importance, especially when monitoring the health of the catalyst bed. Early thrusters were partially disassembled and dewpoint measured after hotfire to ensure dryness of the interior. Based on results, multiple different purge procedures were investigated, and when one was found that consistently yielded no evidence of liquid deposition, it was automated.

5. Case study: A manufacturing challenge

The following is a detailed example of a manufacturing challenge provided to shed light on the failure analysis process.

5.1. Issue summary

Early in the productization program, as initial Ocelot 1.2 units were being tested, an early unit suddenly experienced a structural failure, indicative of loss of oxidization coating health (*Figure 5*). This was surprising because it occurred well within the range of operating conditions that Ocelot units had previously been operated in.

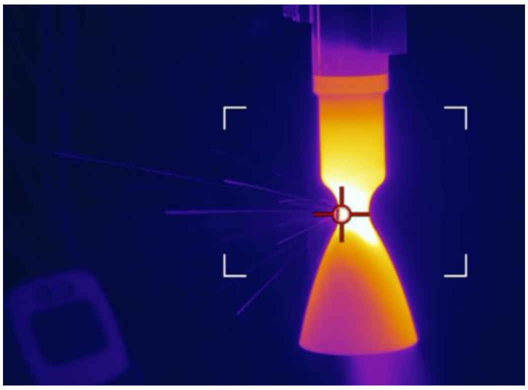

Figure 5: A thruster during the moment of failure

5.2. Approach towards resolution

Identical burn conditions were replicated on other units without indication of failure. Careful attention was paid to the propellant, test stand telemetry and other boundary conditions, and similar conditions were also replicated on other thrusters in BSS's family without issue.

A test series aimed to identify if there was a systematic problem with the thermal measurements that BSS was pulling. Starting from low technology levels, a characterization campaign using multiple sensor types (thermocouples, pyrometers, thermal cameras) was used to better understand actual and realized emissivity; deliberately induced temperature was used for calibration. These tests validated the thermal sensing.

Detailed chemical analysis of the failed chamber was carried out to attempt to identify if an unexpected chemical effect could have caused the higher failure temperature. No such effect was identified.

Unit tests on injectors analyzed whether an off-axis heating profile might be being induced. No such behavior was noted.

Custom CFD was developed to understand possible impacts of shock formation at sea level, coating flow, or similar behavior. No failure mode was identified.

Further units were tested across duration in a continued attempt to replicate. A stochastic failure mode was identified that did not seem directly correlated with runtimes, wall temperatures, or unit serial numbers. Crucially, the thermal data being collected did not replicate across previous production batches of thrusters.

5.3. Root cause

The behavior across batches proved to be the key discovery. Further analysis of the additive manufacturing process for this chamber batch uncovered higher internal surface roughness than had been anticipated.

Immediately, the remainder of the batch was pulled for visual and CT scanning. These measurements confirmed high surface roughness on the interior surface of various thrusters, distributed unevenly. Patterns of roughness closely matched the distribution of excess heating in operation, and multiple units showed "globules" with sizes in excess of the coating thickness.

Thus, the proposed failure mechanism was as follows: increased and uneven roughness increased local heating on the converging section, creating locations of extreme heating above coating life. In addition, high levels of roughness caused local coating thickness variation and freestanding "globules" opened up the possibility of structurally failing altogether. CFD verified the roughness impact on thermal performance.

BSS worked with its supply partner to modify the print and added additional layers of verification on surface roughness. To ensure that the issue had been resolved, multiple thrusters were produced with the new process and taken to life at maximum temperature. Each of them demonstrated good performance and steady operation, with no indication of early stochastic failure.

6. Conclusion

Benchmark hopes that adding some evidence of the magnitude of the problems of productization to the public awareness will help others in the general transition to a space economy where propulsion is an easy, commoditized product.

REFERENCES

[1] Othman, N.; Krishnan, S.; Wan Ali, W.K; Mohd Jaafar, M.N.: Design and testing of a 50N hydrogen peroxide monopropellant rocket thruster, *Jurnal Mekanikal*, 2011, **33**, 70–81

[2] Wernimont, E.; Ventura, M.; Garboden, G.; Mullens, P.: Past and present uses of rocket grade hydrogen peroxide, General Kinetics, 1999 https://www.hydrogen-peroxide.us/history-US-General-Kinetics/H2O2_Conf_1999-Past_Present_Uses_of_Rocket_Grade_Hydrogen_Peroxide.pdf

[3] SMC-S-016:2014 Test requirements for launch, upper-stage and space vehicles (US Air Force Space Command)

[4] Aerojet Rocketdyne - Monopropellant rocket engines

AJRD-LHX_Monopropellant_Rocket_Engines_SpecSheet_CMYK_061423_APPROVED.pdf
(accessed: September 2025)

[5] Aerojet Rocketdyne - AJ10-220 reaction control thruster
https://satcatalog.s3.amazonaws.com/components/1012/SatCatalog_-_Aerojet_Rocketdyne_-_AJ10-220_62.3N_-_Datasheet.pdf
(accessed September 2025)

[6] Rubicon Spapce Systems - Thrusters
https://www.rubicon.space/products-cat/1/thrusters
(accessed: September 2025)

[7] Tóth, T.; Erdélyi, F.; Kulcsár, Gy.: Decision supporting of production planning and control by means of key production performance measuring indicators, in: Proc. 7th Int. Symp. Tools Methods Competit. Eng. (TMCE), Horváth, I.; Rusák, Z. (Eds.) (Delft University of Technology, Delft, Netherlands), 2008, pp. 1201–1215