ICARUS: Design & Experimental Validation of a Modular 1 kN Hybrid Rocket Engine

---

FOR REPEATABLE, HIGH-FIDELITY PROPULSION RESEARCH

The Problem With Conventional Hybrid Rocket Engines

ABLATION UNCERTAINTY: Nozzle erosion varies with each test, introducing experimental inconsistencies and complicating fuel composition and injector design studies.

PERFORMANCE DRIFT: Eroding nozzles increase throat area, reducing chamber pressure and drifting from intended performance.

HIGH COSTS: Single-use nozzles raise testing costs, limiting research scale for smaller institutions.

ICARUS

A highly modular 1kN regeneratively cooled hybrid rocket engine designed to solve the experimental variability issues associated with graphite nozzle and insert architectures.

DESIGN VARIATIONS OF ICARUS (V1, V2, 1KN AEROSPIKE)

Tested Design Stats

Dry Mass:	2.729 ± 0.0001 kg
Empirically Validated Peak Thrust:	916 ± 11N
Empirically Validated Isp:	226 ± 24 s
Throat Deformation:	<0.01mm (over 6 test fires)
Total Impulse:	3357.78 ± 110 N·s
T/W Ratio:	34.2 ± 0.4
Cost Per Engine:	$481.26
Propellant Cost:	$13.26/kg
Assembly Time:	<2 Hours*
Individual Component Replacement Time:	<5 Minutes*

*Design is comprised of flange-joined components, requires no specialized tooling or welding, and can be entirely disassembled and reassembled with 1 M4 allen key in <5 minutes.

Propellants

PROPELLANTS

- N_2O selected for self-pressurization, high decomposition temperature (573 K), and ease of acquisition.
- Fuel grain: 89.8% paraffin / 10% Al/Mg (3 µm, 50:50) / 0.2% graphene nanoplatelets (1–10 nm). Paraffin's high regression rate and droplet entrainment minimizes grain length; Al/Mg raises flame temperature and improves ignition reliability; graphene platelets fill grain voids and reduce cracking risk.
- CEA modeling at O/F = 5.0 yields Isp = 247 s, T_c = 3,264 K, γ = 1.25.
- Phenolic grain casings selected for heat tolerance and cost. Cylindrical port geometry chosen over finocyl/helical designs for manufacturing simplicity.

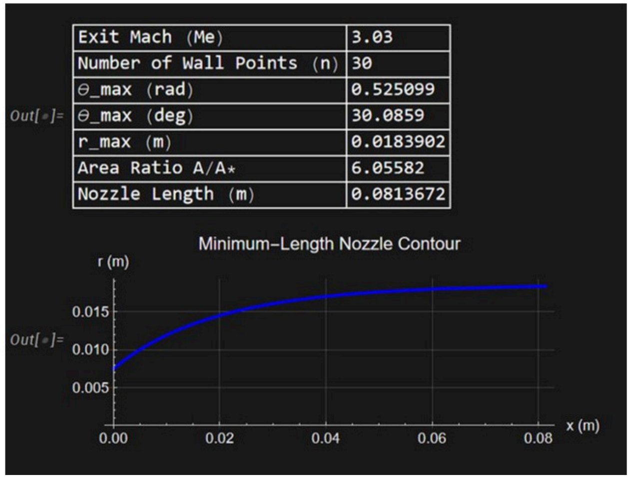
Post-fire, fuel grains (L)

Full fuel grain (R)

Nozzle Design

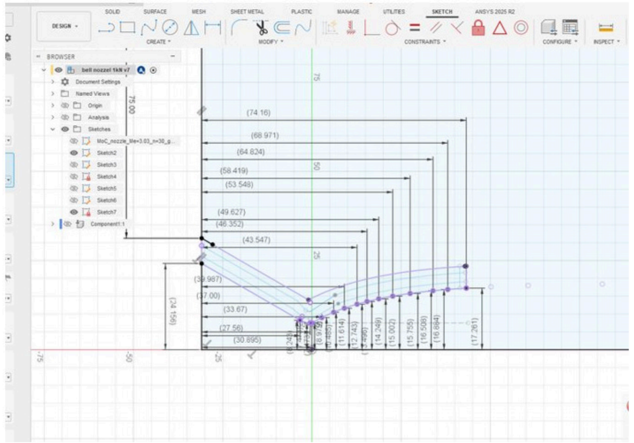
NOZZLE DESIGN

- Chamber pressure of 550 psi and manifold pressure of 900 psi provide a large injector ΔP, improving combustion species mixing, suppressing backflow flame propagation, and ensuring sufficient pressure margin across the regenerative cooling circuit before N_2O flashing onset.
- Engine contour derived from textbook rocket design equations and Stanford hybrid lecture notes, implemented in Excel.
- Nozzle expansion contoured in Mathematica via 80% truncated Prandtl-Meyer method (30 subdivisions); targets ~99% nozzle efficiency per literature.



```
Out[•]= Exit Mach (Me)              3.03
        Number of Wall Points (n)   30
        θ_max (rad)                 0.525099
        θ_max (deg)                 30.0859
        r_max (m)                   0.0183902
        Area Ratio A/A*             6.05582
        Nozzle Length (m)           0.0813672
```

Prandtl-Meyer contour plot



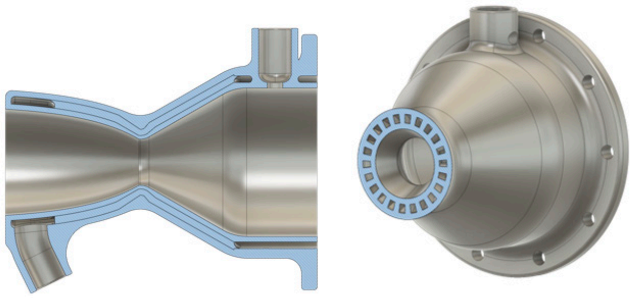
Nozzle contour dimensioned spline nodes

Engine Design (Regen)

ENGINE DESIGN (REGEN)

- Flange joints between nozzle, chamber, and manifold sections seal via 0.5 mm copper alloy crush gaskets (0.5 µm surface finish), providing high-ΔP sealing without permanent bonds and tolerating temperature extremes beyond the range of polymer seals.
- Hybrid regen cooling combines discrete variable-height channels (nozzle) with a coaxial shell design (chamber). The simpler coaxial approach is feasible because the paraffin grain inherently insulates chamber walls during combustion, significantly reducing cost without compromising thermal margins.
- Fuel grain thermal expansion during loading forms a secondary nested seal at all flange junctures.

Coaxial shell assembly



Version 2 nozzle section analysis

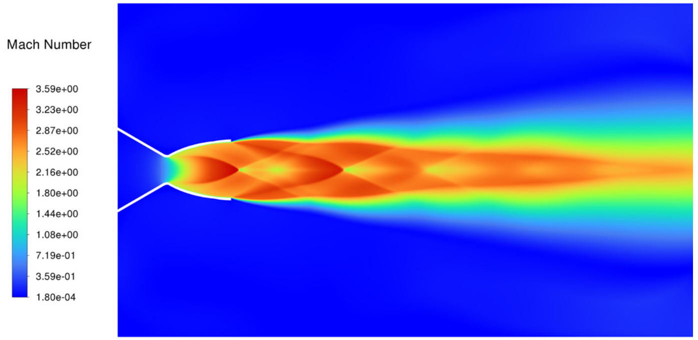
Coaxial shell to nozzle fitting

CFD Verification

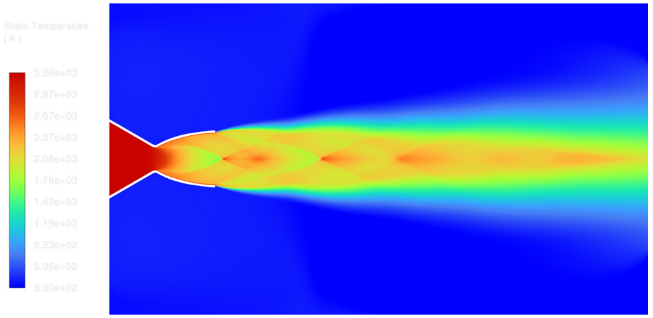
CFD VERIFICATION

- The solution was considered time-converged when all governing-equation residuals exhibited bounded, repeatable oscillations below 1×10^{-4} at a time step of $\Delta t = 1\times10^{-6}$ s. The final solution was conducted over 0.138 s total flow time.
- Simulation yielded 953 N peak thrust, 0.399 kg/s mass flow, and Isp =243 s; consistent with design targets. Slight divergence from CEA and ideal design targets attributed to frozen-flow assumption and pressure thrust.

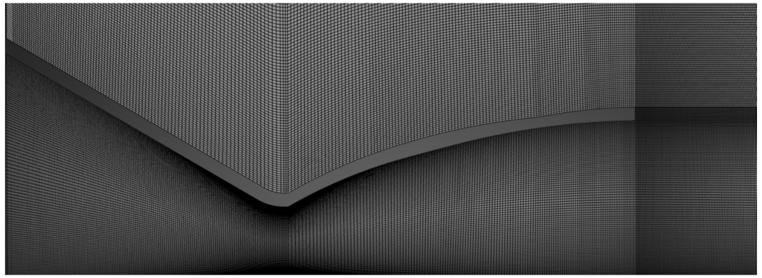
Converged Solution Mach Contours



Converged Solution Temperature Contours



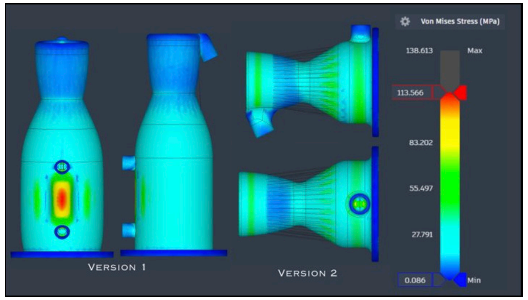
Structured Mesh Used for Simulation

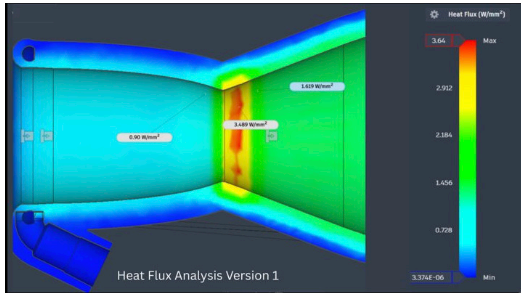


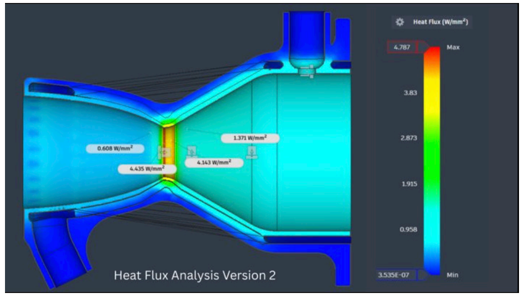
FEA Verification

FEA VERIFICATION

- FEA conducted in Fusion 360 at 1.5× design pressure; nozzle v1 achieved minimum SF = 1.50 (effective SF ~2.25). Nozzle v2 improved this to SF = 1.88 (effective SF ~2.82).
- Wall temperatures derived by mapping peak CFD heat flux across three nozzle subdivisions and associating equivalent heating wattage to each region.
- Regen cooling analyzed via convective heat transfer model; h = 5,000 W/m²K conservatively selected for semi-biphasic, supersaturated N_2O at 20°C. Simplifications (constant h, bulk temperature, and heat flux) were offset by conservative value selection throughout.
- Nozzle v2 cooling improvements increased throat heat flux from 3.64 to 4.87 W/mm², reducing maximum throat temperature by 108°C (779°C → 671°C). This remains a conservative estimate, as increased coolant velocity from channel constriction would likely further reduce throat temperatures.







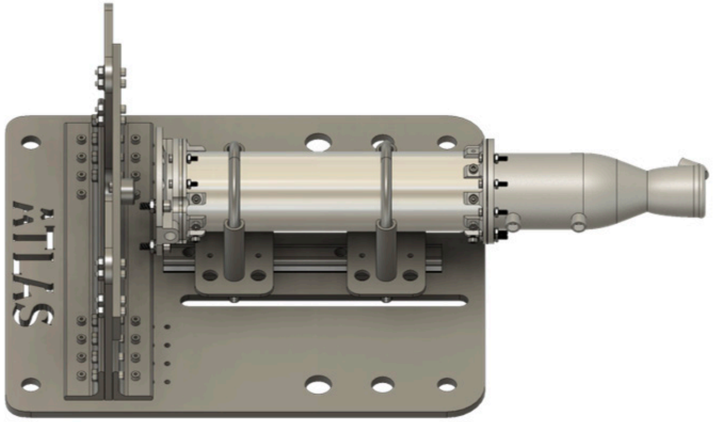
Test Stand Design

TEST STAND DESIGN

- Stand constructed from 0.25” 316L SS and AR500 steel with a high-temperature linear slide; rated to 5 kN (SF = 3) for use beyond this project.
- Plumbing supports N_2O supply and blowdown N_2 purge; features normally-closed solenoids, CGA oxygen-standard cleaned components, redundant check valves, and hardwired physical fallbacks on the N_2 line for electronics failure contingency.
- All tanks recessed into ground wells to restrict shrapnel propagation to skyward only; all plumbing components rated to 2× working pressure.
- Data acquisition: nozzle temperature at 12 Hz, thrust at 320 Hz, chamber pressure via analog gauge video analysis.
- Safety: 250’ minimum standoff, remote purge, and remote disconnect systems.

Test Stand Design

TEST STAND DESIGN



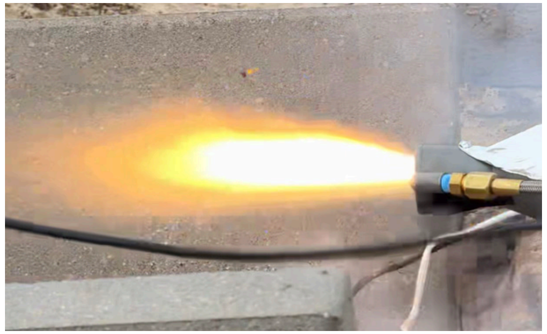
Test stand and engine assembly

Test stand plumbing system (L) and exhaust plume trench (R)

Initial Testing

TEST 1

Peak Thrust: 171 ± 11N
Total Impulse: 428.53 ± 55 N·s
Δ Throat Temp: 38.12 ± 0.25 °C
Throat Deformation: <0.01*
Injector Diameter: 0.06”
Notes: Loose fitting lead to subnominal cooling performance

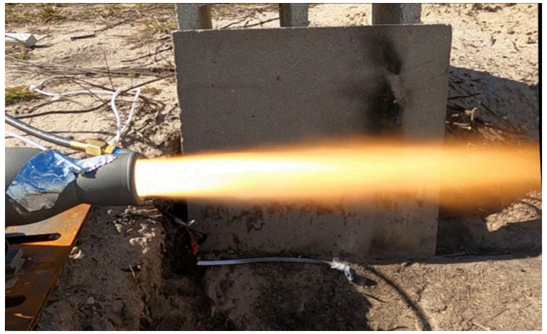


TEST 2

Peak Thrust: 167 ± 11N
Total Impulse: 153.15 ± 55 N·s
Δ Throat Temp: -7.2 ± 0.25 °C
Throat Deformation: <0.01*
Injector Diameter: 0.06”
Notes: Improperly shaped grain resulted in partial grain combustion. Lesser heat flux demonstrated effectiveness of cooling system

TEST 3

Peak Thrust: 187 ± 11N
Total Impulse: 807.74 ± 55 N·s
Δ Throat Temp: 16.53 ± 0.25 °C
Throat Deformation: <0.01*
Injector Diameter: 0.06”
Notes: Leaking flanges; fixed for future tests.



TEST 4

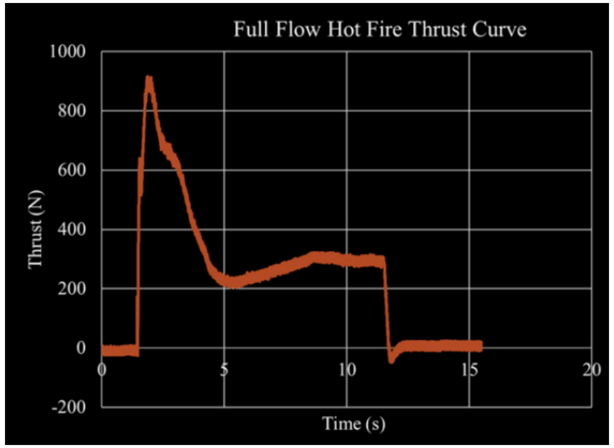
Peak Thrust: 252 ± 11N
Total Impulse: 1160 ± 55 N·s
Max Throat Temp: n/a
Throat Deformation: <0.01*
Injector Diameter: 0.12”
Notes: Loose wire resulted in lost temperature data.

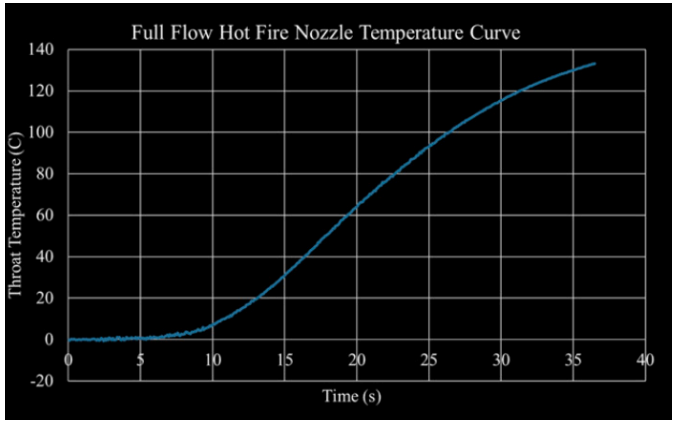
*Throat deformation measure after the removal of 25-50 micron coking formed during testing.
**Maximum temperature include thermal soak after test completion

Full Flow Testing

FULL FLOW TESTING

Peak Thrust:	916 ± 11N
Isp:	226 ± 24 s
Max Throat Temp:	133.19 ± 0.25 °C
Throat Deformation:	<0.01mm
Total Impulse:	3357.78 ± 110 N·s
Analysis:	V1 nozzle expands exhaust less than V2 nozzle, leading to shock diamond formation and lower peak thrust than ideal. Variability in plume luminosity indices O/F shift during grain regression.





***temperature plot includes post-fire thermal soak**

Questions?

PLEASE CONTACT:

agangjee26@sjs.org
algangjee@icloud.com