RPL Rocket Propulsion Laboratory ESTD 2023

Engine Design Report

RPL Engine Workbench v1.0.0 · Rocket Propulsion Laboratory LLC

10 Jul 2026 16:18

Apollo LMAE Reference Case

NTO / Aerozine50 · O/F 1.60 · Pc 0.848 MPa · ε 45.600

Design Warnings — 4 issue(s) detected
First 3 of 4 shown below. Full list with subsystem tags in Section 15.

Warning
Thermochemistry source: Auto mode could not reach the external RocketCEA source (RocketCEA integration script is not available.). Results are using the embedded tabulated CEA source instead of live chemistry. Install the Python venv or select a source explicitly.

Warning
Compressible pressurant path reaches a critical pressure ratio; verify regulator/restriction sizing.

Warning
Compressible gas path reaches the critical pressure ratio across the main restriction; flow may be choked.

... and 1 more — see Section 15 for the complete list.

RESULT STATUS
PRELIMINARY — Embedded CEA reference tables

Solve mode	First-pass sizing
Convergence	One-pass closed-form (Pc and O/F are fixed inputs)
Residuals	n/a — no iteration in this mode
Thermochemistry	tabulated_cea
Transport / species	Transport available; species not available

1 DESIGN INPUTS

Sizing mode [User input]	Target thrust: 15568.0 N
Oxidizer / Fuel [User input]	NTO / Aerozine50
Mixture ratio O/F [User input]	1.600
Chamber pressure Pc [User input]	0.848 MPa
Ambient pressure Pa [User input]	0.000 MPa
Expansion ratio ε = Ae/At [User input]	45.600
Combustion efficiency η_c* [User input]	96.0 %
Nozzle efficiency η_Cf [User input]	98.0 %
Nozzle contour type [User input]	Rao Bell
Nozzle flow model [User input]	Frozen composition
Thermochemistry source [Solver selection]	tabulated_cea
Feed system type [User input]	Regulated (pressurant bottle + regulator)
Burn duration [User input]	30.0 s

2 REACTANTS

Propellant physical properties are used for injector sizing, feed system analysis, and regenerative cooling. Thermochemical properties (Tc, γ, Mw, c*) are from the thermochemistry source.

Oxidizer [User input]	NTO
Oxidizer density [[USAFPH] NTO at 20 °C, 1 atm.]	1441.0 kg/m³
Oxidizer viscosity source	[USAFPH] NTO viscosity.
Fuel [User input]	Aerozine50
Fuel density [[LPIA] A-50 (50 wt% UDMH + 50 wt% N2H4) at 20 °C.]	893.0 kg/m³
Fuel viscosity source	[LPIA] A-50 viscosity.
Oxidizer mass flow [Solver]	3.1722 kg/s
Fuel mass flow [Solver]	1.9826 kg/s
Effective O/F [Solver]	1.600

3 MODEL VALIDITY SUMMARY

Subsystems marked LIMITED or UNAVAILABLE must not be used for design decisions without independent verification. Values that are unavailable are reported as 'Not available from current model' and are not estimated.

SUBSYSTEM	STATUS	NOTES / SOURCE
Thermochemistry (Tc, γ, Mw, c*)	AVAILABLE	tabulated_cea
Nozzle expansion (1-D isentropic)	MODELED	Frozen composition — boundary layer, divergence, and heat loss not modelled
Transport properties (Cp, μ, k, Pr)	AVAILABLE	Available at chamber, throat, exit stations

Species composition (mole/mass fractions)	UNAVAILABLE	Not available from current thermochemistry source; see Section 8
Regenerative cooling	AVAILABLE	Axially zoned thrust-chamber thermal model using station-aware gas properties where available, a Bartz-style gas-side coefficient, Dittus-Boelter coolant-side coefficient, 1-D wall conduction, and Darcy-Weisbach channel pressure drop. Coolant properties: Aerozine-50 at 20 C — first-pass properties Temperature-adjusted to 293.1 K for zoned coolant properties. Axial zoning is resolved as chamber, throat, and nozzle segments with coolant heating carried forward zone-to-zone. Gas-side transport and state properties are pulled from the thermodynamic solver when available. Coolant properties are temperature-adjusted zone-by-zone using the local bulk coolant temperature. Outer jacket thickness is retained as a geometry input for follow-on CAD and structural work; this thermal model uses hot-wall thickness as the primary conduction path.
Feed system (pressure budget)	SCREENING — percenta	Line and valve losses are fixed fractions of Pc, not physics-solved pipe flow. Tank pressure and injector ΔP are calculated from user inputs and model assumptions.
Acoustic combustion stability	ASSESSED	No acoustic coupling flagged — empirical acoustic mode analysis
Nozzle flow separation	ATTACHED	Nozzle is not overexpanded past the fixed-ratio separation screen (p_exit / p_amb = 1560.862, threshold = 0.583).

3.1 FLOWFIELD STUDIO STEADY RESULT / DOMAIN HONESTY

No fresh steady Flowfield Studio result was attached to this report. Stale or transient flowfields are intentionally omitted rather than exported as current steady data.

3.2 FLOWFIELD STUDIO WALL QUALITY

Wall-quality y+ values are preliminary Flowfield Studio diagnostics only. They are not validated RANS, and no turbulence transport equation is solved.

Availability / status	`wall quality unavailable: requires converged viscous wall result`
Basis label	`not available`
Validation status	`not validated RANS`

No y+ values are reported here because wall quality requires a converged viscous wall result. Inviscid, un-marched, non-converged, and wall-less Flowfield Studio runs intentionally export the reason instead of zeros.

4 KEY PERFORMANCE METRICS

Vacuum Isp and vacuum thrust are the headline design metrics. Ambient performance is reported below the cards with flow-regime context. Ambient values are suppressed if flow separation is detected.

15568.0 N Thrust (vacuum)	**308.0 s** Isp (vacuum)	**1616.64 m/s** c*	**5.1548 kg/s** Mass flow
111.86 mm Throat Dt	**755.35 mm** Exit De	**3120.0 K** Tc (chamber)	**0.848 MPa** Pc (chamber)

Nozzle regime at design point [Solver]	`underexpanded`
Isp, ambient [Solver — attached flow, valid]	`307.97 s`
Thrust, ambient [Solver — attached flow, valid]	`15568.0 N`

4.1 ENGINEERING FIDELITY SUMMARY

Quick-reference fidelity status for all model subsystems. Subsystems marked SCREENING or UNAVAILABLE require independent verification before any design decision.

MODEL / SUBSYSTEM	STATUS	FIDELITY NOTE
Thermochemistry (Tc, γ, Mw, c*)	AVAILABLE	tabulated_cea
Feed / cycle model	SCREENING	Regulated (pressurant bottle + regulator) — line/valve losses are % of Pc fractions, not pipe-flow physics
Nozzle flow (1-D isentropic)	MODELED	Frozen composition
Regenerative cooling	AVAILABLE	Bartz / Dittus-Boelter, 3-zone lumped model
Mass budget	SCREENING	Engine: empirical regression ±30%; Tanks: thin-wall hoop stress screening
Species composition	UNAVAILABLE	Not available from current thermochemistry source — run external CEA/Cantera
Transport properties (Cp, μ, k, Pr)	AVAILABLE	Available at chamber, throat, exit from RocketCEA

CFD property package	PARTIAL	Station props: OK Transport: OK Species: missing — see CFD block below
Design warnings	CAUTION: 4	4 total (0 hard) — see Section 15 for full list

4.2 CFD REFERENCE PROPERTIES AVAILABILITY

Specific fields needed for CFD inlet/outlet boundary condition setup. Fields marked NOT AVAILABLE must be obtained from an external CEA or Cantera run before use in a CFD simulation. Formatted CFD input blocks are in Section 7.

Gas-phase model [All stations]	Ideal gas — P = ρ R_specific T
Equation of state [All stations]	Calorically perfect ideal gas
R_specific (chamber) [R_universal / Mw]	380.0 J/kg-K
Station properties (P, T, Ma, γ, R) [Isentropic solver]	Available — 3 stations: chamber, throat, exit
Transport properties (Cp, μ, k, Pr) [Fluid model]	Available at all 3 stations from RocketCEA
Species composition (mole/mass fractions)	NOT AVAILABLE — required for reacting-flow CFD; run external CEA/Cantera

CFD property package: PARTIAL — species composition still needed for reacting-flow CFD

5 THERMOCHEMICAL PERFORMANCE

Thrust, vacuum [tabulated_cea + isentropic nozzle]	15568.0 N
Isp, vacuum [tabulated_cea + isentropic nozzle]	307.97 s
Isp, ambient [Valid — attached flow]	307.97 s
Isp, sea level [Valid — if sea-level regime is attached]	-572.28 s
Thrust, ambient [Valid — attached flow]	15568.0 N
Thrust, sea level [Valid — if sea-level regime is attached]	-28929.4 N
Cf, vacuum [Isentropic nozzle relation]	1.8681
Cf, ambient [Isentropic nozzle relation]	1.8681
Cf, sea level [Isentropic nozzle relation]	-3.4715
c* (characteristic velocity) [tabulated_cea]	1616.64 m/s
Chamber temperature Tc [tabulated_cea]	3120.0 K
Gamma γ (chamber) [tabulated_cea]	1.1900
Molecular weight Mw [tabulated_cea]	21.880 kg/kmol
Gas constant R [Ideal gas: R_u / Mw]	379.99 J/kg-K
Total mass flow ṁ [Solver]	5.1548 kg/s
Oxidizer mass flow [Solver: O/F × ṁ / (1 + O/F)]	3.1722 kg/s
Fuel mass flow [Solver: ṁ / (1 + O/F)]	1.9826 kg/s
Combustion efficiency η_c* [User input]	96.0 %
Nozzle efficiency η_Cf [User input]	98.0 %

6A CHAMBER GAS STATE

Pressure [tabulated_cea / isentropic]	0.848 MPa
Pressure ratio P/Pc [Isentropic]	1.00000
Temperature [tabulated_cea / isentropic]	3120.0 K
Gamma γ [tabulated_cea]	1.1900
Molecular weight [tabulated_cea]	21.880 kg/kmol
Gas constant R [Ideal gas: R_u / Mw]	379.99 J/kg-K
Mach number [Isentropic area-Mach relation]	0.000
Cp [Transport model]	2380.0 J/kg-K
Dynamic viscosity μ [Transport model]	8.400e-05 Pa-s
Thermal conductivity k [Transport model]	0.3635 W/m-K
Prandtl number Pr [Cp × μ / k]	0.5500
Isentropic bulk modulus K_s = γ × P [Ideal gas relation]	1.0091e+06 Pa

6B THROAT GAS STATE

Pressure [tabulated_cea / isentropic]	0.480 MPa
Pressure ratio P/Pc [Isentropic]	0.56643
Temperature [tabulated_cea / isentropic]	2849.3 K
Gamma γ [tabulated_cea]	1.1900
Molecular weight [tabulated_cea]	21.880 kg/kmol
Gas constant R [Ideal gas: R_u / Mw]	379.99 J/kg-K
Mach number [Isentropic area-Mach relation]	1.000

Cp [Transport model]	2380.0 J/kg-K
Dynamic viscosity μ [Transport model]	7.883e-05 Pa-s
Thermal conductivity k [Transport model]	0.3411 W/m-K
Prandtl number Pr [Cp × μ / k]	0.5500
Isentropic bulk modulus K_s = γ × P [Ideal gas relation]	5.7159e+05 Pa

6C EXIT GAS STATE

Pressure [tabulated_cea / isentropic]	0.002 MPa
Pressure ratio P/Pc [Isentropic]	0.00184
Temperature [tabulated_cea / isentropic]	1141.5 K
Gamma γ [tabulated_cea]	1.1900
Molecular weight [tabulated_cea]	21.880 kg/kmol
Gas constant R [Ideal gas: R_u / Mw]	379.99 J/kg-K
Mach number [Isentropic area-Mach relation]	4.271
Cp [Transport model]	2380.0 J/kg-K
Dynamic viscosity μ [Transport model]	4.155e-05 Pa-s
Thermal conductivity k [Transport model]	0.1798 W/m-K
Prandtl number Pr [Cp × μ / k]	0.5500
Isentropic bulk modulus K_s = γ × P [Ideal gas relation]	1.8574e+03 Pa

7 CFD REFERENCE MATERIAL BLOCKS

These blocks are formatted for CFD inlet/outlet boundary condition setup. All values are in SI units. Transport properties are included when available. Fields marked NOT AVAILABLE must be obtained from an independent source before use in a CFD simulation. Do not use liquid-phase bulk modulus for gas-phase compressibility. The isentropic bulk modulus K_s = γ × P is the correct compressibility input for ideal gas CFD.

7A CFD BLOCK — CHAMBER (INLET BC)

// Pressure BC [Solver — isentropic station]	P = 8.4800e+05 Pa
// Temperature BC [Solver — isentropic station]	T = 3120.0 K
// Mach number [Isentropic area-Mach relation]	Ma = 0.0000
// Ratio of specific heats [Thermochemistry source]	γ = 1.1900
// Specific gas constant (R = R_u / Mw) [Ideal gas]	R = 379.99 J/kg·K
// Density [ρ = P / (R T) — ideal gas]	ρ = 7.1526e-01 kg/m³
// Speed of sound [a = √(γ R T)]	a = 1187.8 m/s
// Bulk velocity [V = Ma × a]	V = 0.0 m/s
// Isentropic bulk modulus [K_s = γ × P — use for ideal-gas CFD compressibility]	K_s = 1.0091e+06 Pa
// Specific heat Cp [Transport model / Sutherland scaling]	Cp = 2380.0 J/kg·K
// Dynamic viscosity [Transport model / Sutherland scaling]	μ = 8.400e-05 Pa·s
// Thermal conductivity [Transport model / Sutherland scaling]	k = 0.36349 W/m·K
// Prandtl number [Cp × μ / k]	Pr = 0.5500
// Species composition (mole/mass fractions)	NOT AVAILABLE for this station — run external CEA or Cantera for reacting-flow CFD

7B CFD BLOCK — THROAT (CRITICAL SECTION)

// Pressure BC [Solver — isentropic station]	P = 4.8033e+05 Pa
// Temperature BC [Solver — isentropic station]	T = 2849.3 K
// Mach number [Isentropic area-Mach relation]	Ma = 1.0000
// Ratio of specific heats [Thermochemistry source]	γ = 1.1900
// Specific gas constant (R = R_u / Mw) [Ideal gas]	R = 379.99 J/kg·K
// Density [ρ = P / (R T) — ideal gas]	ρ = 4.4363e-01 kg/m³
// Speed of sound [a = √(γ R T)]	a = 1135.1 m/s
// Bulk velocity [V = Ma × a]	V = 1135.1 m/s
// Isentropic bulk modulus [K_s = γ × P — use for ideal-gas CFD compressibility]	K_s = 5.7159e+05 Pa
// Specific heat Cp [Transport model / Sutherland scaling]	Cp = 2380.0 J/kg·K
// Dynamic viscosity [Transport model / Sutherland scaling]	μ = 7.883e-05 Pa·s
// Thermal conductivity [Transport model / Sutherland scaling]	k = 0.34111 W/m·K
// Prandtl number [Cp × μ / k]	Pr = 0.5500
// Species composition (mole/mass fractions)	NOT AVAILABLE for this station — run external CEA or Cantera for reacting-flow CFD

7C CFD BLOCK — EXIT (OUTLET BC)

// Pressure BC [Solver — isentropic station]	P = 1.5609e+03 Pa
// Temperature BC [Solver — isentropic station]	T = 1141.5 K
// Mach number [Isentropic area-Mach relation]	Ma = 4.2714
// Ratio of specific heats [Thermochemistry source]	γ = 1.1900
// Specific gas constant (R = R_u / Mw) [Ideal gas]	R = 379.99 J/kg·K
// Density [ρ = P / (R T) — ideal gas]	ρ = 3.5985e-03 kg/m³
// Speed of sound [a = √(γ R T)]	a = 718.4 m/s
// Bulk velocity [V = Ma × a]	V = 3068.8 m/s
// Isentropic bulk modulus [K_s = γ × P — use for ideal-gas CFD compressibility]	K_s = 1.8574e+03 Pa
// Specific heat Cp [Transport model / Sutherland scaling]	Cp = 2380.0 J/kg·K
// Dynamic viscosity [Transport model / Sutherland scaling]	μ = 4.155e-05 Pa·s
// Thermal conductivity [Transport model / Sutherland scaling]	k = 0.17981 W/m·K
// Prandtl number [Cp × μ / k]	Pr = 0.5500
// Species composition (mole/mass fractions)	NOT AVAILABLE for this station — run external CEA or Cantera for reacting-flow CFD

8 COMBUSTION PRODUCT SPECIES COMPOSITION

Species composition is NOT AVAILABLE from the embedded CEA table source, which provides Tc, γ, Mw, and c* from pre-computed lookup tables only. Select RocketCEA (full equilibrium chemistry mode) for per-station species composition.

Propellants	NTO / Aerozine50
O/F (by mass)	1.6000
Chamber pressure	0.848 MPa
Expansion ratio	45.6000

Species fields in Section 7 (CFD blocks) are marked NOT AVAILABLE and must be filled from an external CEA/Cantera run before use in reacting-flow CFD.

9 NOZZLE AND CHAMBER GEOMETRY

Nozzle contour [User input]	Rao Bell
Chamber diameter Dc [Solver: Ac/At × Dt]	183.80 mm
Throat diameter Dt [Solver: sizing mode]	111.86 mm
Exit diameter De [Solver: ε × At = Ae]	755.35 mm
Expansion ratio ε = Ae/At [Solver]	45.600
Contraction ratio Ac/At [User input]	2.70
Chamber length Lc [L* characteristic length method]	296.30 mm
Nozzle length Ln [Contour geometry / bell fraction]	960.62 mm
Throat blend radius [JANNAF standard: 1.5×Rt upstream, 0.382×Rt downstream]	55.93 mm
Converging angle θ [User input]	45.0°
Diverging half-angle α/α_e [User input]	8.0°
L* (characteristic length) [User input]	80 cm
Bell / TIC length fraction [User input]	0.800

10 OFF-DESIGN NOZZLE ANALYSIS

Absolute vacuum selected (ambient pressure = 0). A finite matched expansion ratio does not exist because Pe = 0 would require infinite expansion. The ideal unconstrained vacuum solution tends toward infinite ε; the expansion ratio was selected using a finite design constraint: Maximum expansion ratio.

Exit Mach Me [Isentropic area-Mach relation]	4.271
Exit pressure Pe [Isentropic]	0.002 MPa
Exit pressure ratio Pe/Pc [Isentropic]	0.00184
Ambient pressure Pa [Solved project]	0.000 MPa
Exit-to-ambient pressure ratio Pe/Pa [Diagnostic]	Not finite for Pa <= 0
Expansion classification [Diagnostic]	vacuum_unbounded

Vacuum or non-positive ambient pressure: a finite Pe = Pa matched expansion ratio does not exist. The current finite Ae/At is a design-limited vacuum nozzle.

Warning: Auto expand-to-Pa is unbounded for Pa <= 0; use an explicit finite vacuum constraint.

Expansion basis: Evaluated after solve using final Pc = 848000.0 Pa, user/design ambient Pa = 0.0 Pa, Pe from the final nozzle expansion, and Ae/At = 45.6000.

Optimum ambient pressure (Pe = Pa for matched) [Isentropic]	0.002 MPa
Nozzle regime at design ambient [Solver]	underexpanded
Thrust at current ambient [Valid — attached flow]	15568.0 N

Thrust at sea level (101325 Pa) [Valid if sea-level is attached]	-28929.4 N
Isp, ambient [Valid — attached flow]	307.97 s
Isp, sea level [Valid if sea-level is attached]	-572.28 s

Separation analysis: Nozzle is not overexpanded past the fixed-ratio separation screen (p_exit / p_amb = 1560.862, threshold = 0.583).

Variable key: Psep = wall static pressure at predicted separation location (Pa). epsSep = local expansion ratio Ae_sep/At at separation point (dimensionless). x/Ln = fractional axial position along nozzle contour length.

11 FEED SYSTEM PRESSURE BUDGET

Feed system losses are treated as boundary conditions or user estimates. For highest-fidelity prediction, use measured injector inlet pressures and measured flow data from testing.

Feed system type [User input]	Regulated (pressurant bottle + regulator)
Chamber pressure Pc [User input]	0.848 MPa
Injector pressure drop ΔP_inj / Pc [User input — percentage of Pc]	20.0 %
Injector inlet pressure P_inj [Solver: Pc × (1 + ΔP/Pc)]	1.018 MPa
Line losses ΔP_line [Estimate: 8% of Pc — not physics-solved]	0.068 MPa
Valve losses ΔP_valve [Estimate: 4% of Pc — not physics-solved]	0.034 MPa
Tank margin fraction [User input]	5.0 %
Required supply pressure (feed tank minimum) [Solver]	1.175 MPa
Ambient pressure Pa [User input]	0.000 MPa

NOTE: Line and valve losses are fixed fractions of Pc, not physics-solved incompressible pipe flow. For accurate feed line pressure drop, perform a separate Darcy-Weisbach or similar analysis and replace these estimates.

Feed System Warning
Compressible pressurant path reaches a critical pressure ratio; verify regulator/restriction sizing.

OXIDIZER FEED PATH

Model [Source]	Single-phase incompressible station model

Model description: Tank -> line -> valve -> manifold -> injector inlet. Liquid properties from propellant deck; reference line diameter inferred from nominal velocity.

Tank outlet — Pressure	1.175 MPa
Tank outlet — Phase / regime	single-phase liquid
Tank outlet — Bulk velocity	12.00 m/s
Tank outlet — Mach	0.010
Tank outlet — Reynolds	629226

Tank outlet note: Reference line diameter inferred from 12.0 m/s nominal bulk velocity.

After line — Pressure	1.128 MPa
After line — Phase / regime	single-phase liquid
After line — Bulk velocity	12.00 m/s
After line — Mach	0.010
After line — Reynolds	629226
After line — ΔP	0.047 MPa

After line note: Distributed Darcy/minor losses lumped into line segment.

After valve — Pressure	1.094 MPa
After valve — Phase / regime	single-phase liquid
After valve — Bulk velocity	12.00 m/s
After valve — Mach	0.010
After valve — Reynolds	629226
After valve — ΔP	0.034 MPa

After valve note: Valve/fitting losses applied across control element.

Injector inlet — Pressure	1.018 MPa
Injector inlet — Phase / regime	single-phase liquid
Injector inlet — Bulk velocity	12.00 m/s
Injector inlet — Mach	0.010
Injector inlet — Reynolds	629226
Injector inlet — ΔP	0.020 MPa

Injector inlet note: Residual manifold loss applied to reach injector inlet condition.

FUEL FEED PATH

Model [Source]	Single-phase incompressible station model

Model description: Tank -> line -> valve -> manifold -> injector inlet. Liquid properties from propellant deck; reference line diameter inferred from nominal velocity.

Tank outlet — Pressure	1.175 MPa
Tank outlet — Phase / regime	single-phase liquid

Tank outlet — Bulk velocity	8.00 m/s
Tank outlet — Mach	0.007
Tank outlet — Reynolds	194623

Tank outlet note: Reference line diameter inferred from 8.0 m/s nominal bulk velocity.

After line — Pressure	1.128 MPa
After line — Phase / regime	single-phase liquid
After line — Bulk velocity	8.00 m/s
After line — Mach	0.007
After line — Reynolds	194623
After line — ΔP	0.047 MPa

After line note: Distributed Darcy/minor losses lumped into line segment.

After valve — Pressure	1.094 MPa
After valve — Phase / regime	single-phase liquid
After valve — Bulk velocity	8.00 m/s
After valve — Mach	0.007
After valve — Reynolds	194623
After valve — ΔP	0.034 MPa

After valve note: Valve/fitting losses applied across control element.

Injector inlet — Pressure	1.018 MPa
Injector inlet — Phase / regime	single-phase liquid
Injector inlet — Bulk velocity	8.00 m/s
Injector inlet — Mach	0.007
Injector inlet — Reynolds	194623
Injector inlet — ΔP	0.020 MPa

Injector inlet note: Residual manifold loss applied to reach injector inlet condition.

PRESSURANT PATH

Model [Source]	Regulated pressurant ideal-gas path

Model description: Bottle -> regulator -> tank using ideal-gas compressible screening and derived pressurant demand from displaced propellant volume.

FIDELITY NOTE: Pressurant path uses a regulated pressurant ideal-gas screening model. Regulator dynamics, choked-flow segments, downstream Mach numbers, and regulator/restriction orifice sizing are NOT solved. If any station in this path is at or near choked conditions, a separate isentropic orifice sizing analysis is required.

Path Warning
Compressible gas path reaches the critical pressure ratio across the main restriction; flow may be choked.

NOTE: This path contains compressible flow segments. Use isentropic bulk modulus $K_s = \gamma P$ for compressibility — do not use liquid-phase bulk modulus.

Pressurant bottle outlet — Pressure	30.000 MPa
Pressurant bottle outlet — Phase / regime	single-phase gas
Pressurant bottle outlet — Bulk velocity	150.81 m/s
Pressurant bottle outlet — Mach	0.150
Pressurant bottle outlet — Reynolds	458445

Pressurant bottle outlet note: Reference gas line area inferred from nominal inlet Mach 0.15.

Regulator inlet — Pressure	30.000 MPa
Regulator inlet — Phase / regime	single-phase gas
Regulator inlet — Bulk velocity	150.81 m/s
Regulator inlet — Mach	0.150
Regulator inlet — Reynolds	458445

Regulator inlet note: Distributed line loss resolved on compressible gas path.

Regulator outlet / downstream restriction — Pressure	1.650 MPa
Regulator outlet / downstream restriction — Phase / regime	single-phase gas
Regulator outlet / downstream restriction — Bulk velocity	2741.93 m/s
Regulator outlet / downstream restriction — Mach	2.727
Regulator outlet / downstream restriction — Reynolds	458445
Regulator outlet / downstream restriction — ΔP	28.350 MPa

Regulator outlet / downstream restriction note: Critical pressure ratio exceeded across main restriction; choked-flow risk flagged.

Propellant tank ullage inlet — Pressure	1.650 MPa
Propellant tank ullage inlet — Phase / regime	single-phase gas
Propellant tank ullage inlet — Bulk velocity	2741.93 m/s
Propellant tank ullage inlet — Mach	2.727
Propellant tank ullage inlet — Reynolds	458445

Propellant tank ullage inlet note: Residual manifold loss applied to injector supply station.

12 THERMAL AND REGENERATIVE COOLING

THERMAL FEASIBILITY STATUS
PASS — coolant ΔP within feed pressure budget
Coolant ΔP: 0.587 MPa | Available supply: 1.175 MPa | Ratio ΔP/P_supply: 0.50

Coolant stream [User input]	Fuel
Wall material [User input]	Inconel625
Wall thermal conductivity [Material database]	14.00 W/m-K
Hot-wall thickness [User input]	1.50 mm
Channel count [User input]	48
Channel width [User input]	2.00 mm
Channel depth [User input]	2.50 mm
Land width [User input]	1.00 mm
Outer jacket thickness [User input]	1.50 mm
Coolant inlet temperature [User input]	293.1 K
Hydraulic diameter Dh [Channel geometry]	2.22 mm
Coolant mass flow [Solver: from engine flow + O/F]	1.9826 kg/s
Coolant bulk velocity [Continuity]	10.42 m/s
Coolant Reynolds number [Re = ρvDh/μ]	30596
Coolant Cp [Fluid database]	2634 J/kg-K
Coolant k [Fluid database]	0.1677 W/m-K
Coolant Pr [Cp × μ / k]	9.426
Gas-side h [Bartz correlation]	3153 W/m²-K
Coolant-side h [Dittus-Boelter]	16645 W/m²-K
Throat heat flux [Bartz]	4.896 MW/m²
Average heat flux [Bartz integrated]	0.739 MW/m²
Total heat load [Bartz integrated over wetted area]	1153.0 kW
Hot-gas wall temperature [Solver: 1-D wall conduction]	1251.6 K
Coolant-side wall temperature [Solver]	727.1 K
Coolant outlet temperature [Solver: energy balance]	518.2 K
Coolant pressure drop [Darcy-Weisbach approximation]	0.587 MPa

IMPORTANT: Coolant pressure drop (0.587 MPa) is NOT included in the feed system pressure budget above. Add this to the required tank pressure when performing feed system sizing.

Film cooling [User input]	Disabled — no film-cooling reduction applied
Chamber zone heat flux [Bartz]	4.130 MW/m²
Throat zone heat flux [Bartz]	4.896 MW/m²
Nozzle zone heat flux [Bartz]	0.289 MW/m²
Chamber coolant outlet [Energy balance]	432.9 K
Throat coolant outlet [Energy balance]	442.1 K
Nozzle coolant outlet [Energy balance]	518.2 K

IMPORTANT: Coolant pressure drop (0.587 MPa) is not included in the feed system pressure budget in Section 11. Add this to the required supply pressure when performing feed system sizing.

Thermal model: Axially zoned thrust-chamber thermal model using station-aware gas properties where available, a Bartz-style gas-side coefficient, Dittus-Boelter coolant-side coefficient, 1-D wall conduction, and Darcy-Weisbach channel pressure drop. Coolant properties: Aerozine-50 at 20 C — first-pass properties Temperature-adjusted to 293.1 K for zoned coolant properties. Axial zoning is resolved as chamber, throat, and nozzle segments with coolant heating carried forward zone-to-zone. Gas-side transport and state properties are pulled from the thermodynamic solver when available. Coolant properties are temperature-adjusted zone-by-zone using the local bulk coolant temperature. Outer jacket thickness is retained as a geometry input for follow-on CAD and structural work; this thermal model uses hot-wall thickness as the primary conduction path.

Thermal Warning
Estimated coolant temperature rise is high. Review channel sizing, coolant choice, and wall thickness before using this geometry for hardware decisions.

13 INJECTOR DESIGN

Pattern [User input]	unlike_doublet
Oxidizer orifice count [User input]	16
Fuel orifice count [User input]	16
Oxidizer orifice diameter [User input / solver]	3.78 mm
Fuel orifice diameter [User input / solver]	3.37 mm
Oxidizer Cd [User input]	0.800

Fuel Cd [User input]	0.800
Oxidizer ΔP / Pc [Solver: Bernoulli + Cd]	20.00 %
Fuel ΔP / Pc [Solver: Bernoulli + Cd]	20.00 %
Oxidizer injection velocity [Solver: Bernoulli]	12.27 m/s
Fuel injection velocity [Solver: Bernoulli]	15.59 m/s
Oxidizer Reynolds number [Re = ρvd/μ]	159092
Fuel Reynolds number [Re = ρvd/μ]	67926
Momentum flux ratio J = (ρv²)_ox / (ρv²)_f [Solver]	1.260
Estimated spray deflection [Empirical: J correlation]	3.79°
Injector face OD [Solver: chamber OD × 0.9 or user override]	165.42 mm
Element pitch [Geometry]	25.98 mm
Face packing fraction [Geometry: Σ(orifice area) / face area]	1.5 %

Bernoulli orifice model: ΔP = (ρv²) / (2 Cd²). Does not account for two-phase flow, manifold distribution effects, or cavitation.

14 ACOUSTIC COMBUSTION STABILITY

Assessment [Empirical acoustic mode coupling]	No acoustic coupling flagged
Speed of sound in chamber gas [Ideal gas: γRT]	1187.79 m/s
Oxidizer injection frequency [Solver]	958.9 Hz
Fuel injection frequency [Solver]	1392.1 Hz
Mode 1L [Acoustic analysis]	2004.4 Hz
Mode 1T [Acoustic analysis]	3787.4 Hz
Mode 2T [Acoustic analysis]	6282.6 Hz
Mode 1R [Acoustic analysis]	7881.9 Hz

No injection–acoustic coupling detected within 30 % bandwidth.
Note: this is a first-principles acoustic screening only — it checks injection frequency proximity to classical cylindrical chamber modes (1L, 1T, 2T, 1R). It does not predict combustion instability. Full stability assessment requires dedicated tools (e.g., NASTRAN, COMSOL, or an empirical stability correlation).

15 DESIGN WARNINGS (FULL LIST)

4 warning(s) generated during this solve. Each warning is shown as a separate card below with its subsystem. A count summary also appears near the front of this report.

Warning — Thermochemistry
Severity: Warning · Subsystem: Thermochemistry
Message: Thermochemistry source: Auto mode could not reach the external RocketCEA source (RocketCEA integration script is not available.). Results are using the embedded tabulated CEA source instead of live chemistry. Install the Python venv or select a source explicitly.
Action: Select RocketCEA for higher-fidelity thermochemical data.

Warning — General
Severity: Warning · Subsystem: General
Message: Compressible pressurant path reaches a critical pressure ratio; verify regulator/restriction sizing.
Action: Review input parameters and verify design margins.

Warning — General
Severity: Warning · Subsystem: General
Message: Compressible gas path reaches the critical pressure ratio across the main restriction; flow may be choked.
Action: Review input parameters and verify design margins.

Warning — Nozzle
Severity: Warning · Subsystem: Nozzle
Message: NOZZLE EXPANSION — Auto expand-to-Pa is unbounded for Pa <= 0; use an explicit finite vacuum constraint.
Action: Adjust expansion ratio or operating altitude to correct nozzle flow regime.

16 SYSTEM MASS BUDGET

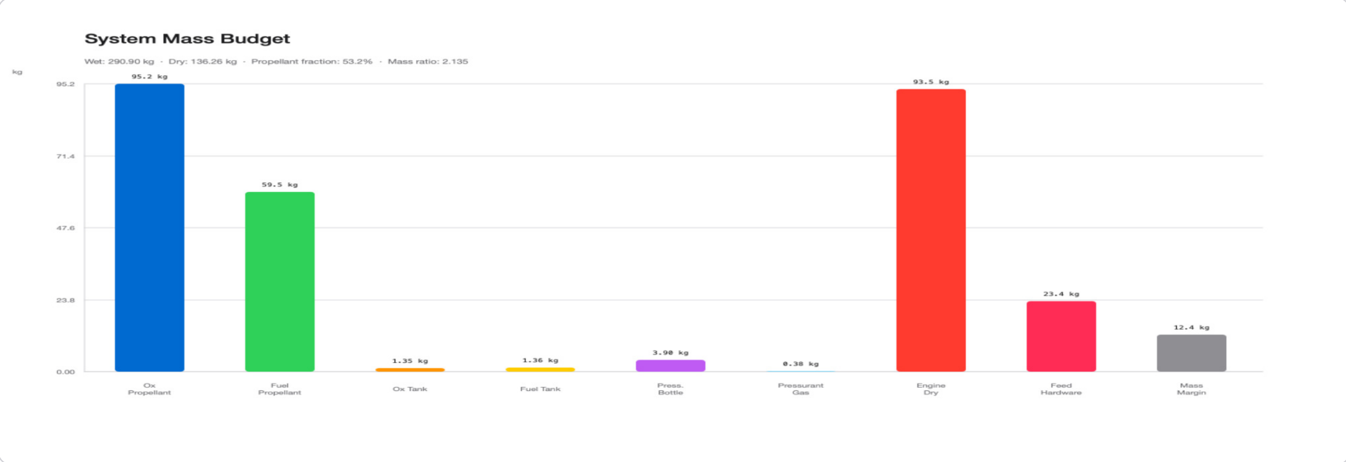
Mass budget completeness: SCREENING ESTIMATE. Tank structural mass uses thin-wall hoop stress (first-pass). Engine dry mass uses empirical regression (±30%). Feed hardware uses a fraction of engine dry mass (user-set). Independent verification required before committing to hardware.

290.9 kg	136.3 kg	53.2 %	2.135
Wet mass	Dry mass	Propellant fraction	Mass ratio (Wet/Dry)

Oxidizer propellant [Solver: mass flow × burn time]	95.17 kg
Fuel propellant [Solver]	59.48 kg
Total propellant [Sum]	154.64 kg
Pressurant gas (onboard at burnout) [Pressurization model]	0.38 kg

Oxidizer tank structural [Thin-wall hoop stress screening: P × r / t]	1.35 kg
Fuel tank structural [Thin-wall hoop stress screening]	1.36 kg
Pressurant bottle structural [Thin-wall screening model]	3.90 kg
Total tank structural [Sum]	6.61 kg
Engine dry mass [Empirical regression from thrust — screening estimate, ±30%]	93.50 kg
Feed hardware [Empirical screening estimate: fraction of engine dry mass]	23.38 kg
Dry mass subtotal (no margin) [Sum]	123.87 kg
Mass margin [User input fraction × dry subtotal]	12.39 kg
Total dry mass [Sum]	136.26 kg
Total wet mass [Sum]	290.90 kg

MASS DISTRIBUTION CHART



17 MODEL ASSUMPTIONS AND DATA SOURCES

Thermodynamics source: tabulated_cea

Nozzle flow model: frozen

Performance source: Embedded tabulated CEA source — NTO + Aerozine50. LPIA CPIA/M5 + Sutton RPE9 + NASA CEA2; Pc = 6.895 MPa. Frozen-flow nozzle, infinite-area combustor assumption. Auto mode: RocketCEA unavailable, fell back to embedded table. [One-pass solver: Pc and O/F are fixed user inputs; feed ΔP closure is not iterated back to Pc. Suitable for preliminary sizing.]

Solver closure: one-pass closed-form (Pc and O/F are fixed user inputs — no iteration required).

Result fidelity level: Embedded CEA reference tables.

Infinite Area Combustor (IAC): injector-face gas velocity is neglected; total enthalpy at the combustion chamber equals the adiabatic flame enthalpy. This is the standard assumption for preliminary liquid rocket engine design.

Frozen-flow nozzle expansion: combustion product composition is fixed at the throat. This is a conservative assumption — equilibrium-flow Isp is typically 1–3% higher.

1-D isentropic nozzle: boundary-layer displacement, divergence losses, and heat-transfer losses are not modelled in the performance calculation. These effects are accounted for by the user-supplied efficiency factors η_{c^*} and η_{Cf}.

Oxidizer density source: [USAFPH] NTO at 20 °C, 1 atm.

Fuel density source: [LPIA] A-50 (50 wt% UDMH + 50 wt% N_2H_4) at 20 °C.

Oxidizer viscosity source: [USAFPH] NTO viscosity.

Fuel viscosity source: [LPIA] A-50 viscosity.

Tank structural mass: thin-wall hoop stress model, $\sigma = P \cdot r/t$. Safety factor and fitting factor applied from user inputs. Does not account for weld joints, access ports, or end-cap stress concentrations.

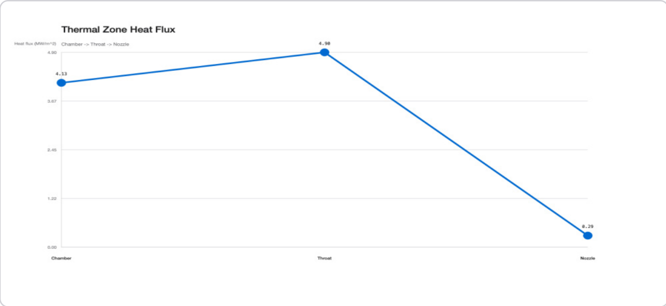
Engine dry mass: empirical regression based on thrust level and propellant class. Accuracy is ±30% for preliminary design. Actual mass depends on design choices.

Injector pressure drop: Bernoulli orifice model with user Cd. Does not account for two-phase flow, cavitation, or manifold distribution.

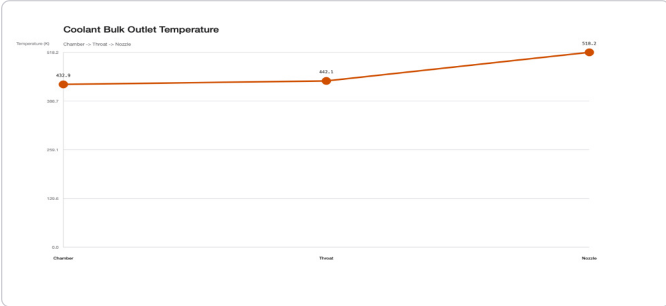
Thermal model: Bartz correlation for gas-side heat transfer; Dittus-Boelter for coolant-side forced convection; three-zone (chamber / throat / nozzle) lumped analysis. Coolant properties from built-in fluid database.

Model source: Axially zoned thrust-chamber thermal model using station-aware gas properties where available, a Bartz-style gas-side coefficient, Dittus-Boelter coolant-side coefficient, 1-D wall conduction, and Darcy-Weisbach channel pressure drop. Coolant properties: Aerozine-50 at 20 C — first-pass properties Temperature-adjusted to 293.1 K for zoned coolant properties. Axial zoning is resolved as chamber, throat, and nozzle segments with coolant heating carried forward zone-to-zone. Gas-side transport and state properties are pulled from the thermodynamic solver when available. Coolant properties are temperature-adjusted zone-by-zone using the local bulk coolant temperature. Outer jacket thickness is retained as a geometry input for follow-on CAD and structural work; this thermal model uses hot-wall thickness as the primary conduction path.

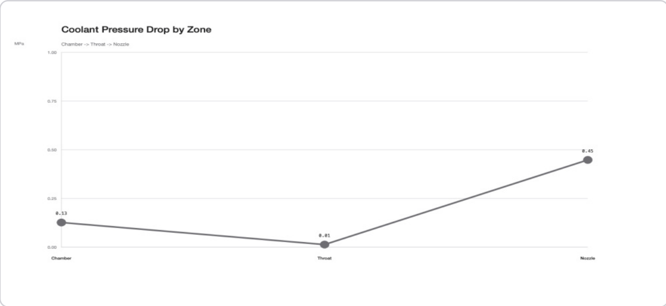
HEAT FLUX



COOLANT TEMPERATURE



COOLANT PRESSURE DROP



WALL TEMPERATURE