RACE2SPACE 2026

HOT-FIRE TEST ANALYSIS

Kimchi
Propulsion Systems(?)

Ignition Development, Test-by-Test Analysis, and Injector Pressure-Drop Assessment of the Kimchi Engine

Final Technical Report

Kimchi Engine Team

Campaign records:	20260622-102, -106 through -112
Propellants:	LOX / IPA
Test location:	AEL J1 Test Facility

1 EXECUTIVE SUMMARY

The Kimchi Engine campaign consisted of eight LOX/IPA hot-fire attempts. Test 1 produced only a weak flame because the J1 stand configuration contained an error: the stand had not been operated recently, and Kimchi was the first test article in the campaign. Tests 2–6 produced no visible flame. Test 7 produced a short burn with visible Mach diamonds, and Test 8 completed a sustained 13 s firing and reached a stable operating state.

The early campaign showed that mass-flow delivery alone was not sufficient for ignition. Tests 2–4 formed both propellant flows while chamber pressure remained below 0.2 bar. Tests 5 and 6 developed progressively stronger chamber-pressure responses without visible flame. The persistent hardware weakness was the injector sizing method. The minimum pressure-drop requirement was applied at the maximum operating point instead of the minimum-throttle point, producing excessive orifice area, low pressure margin, weak atomization, and poor control of jet impingement and mixing.

Test 8 reached 14.05±0.18 bar(g) chamber pressure and 1194±33 N load-cell response over the 4.0–12.5 s steady window. Measured LOX/IPA flow was 0.450/0.250 kg/s, O/F was 1.80, and effective Isp was 173.8 s. The startup instability was driven primarily by oxidizer-rich mixture formation while LOX flow developed faster than IPA flow. A 22 Hz pressure component followed feed-system coupling, while the recurring 78–83 Hz load response belonged to the test-stand/load-cell structural path.

1.1 Scope and configuration

The pressure-fed engine used a throttleable impinging injector, an Inconel 718 chamber and nozzle, and a regenerative fuel path. The design review defined a 1300 N, 15 bar point, a 40–100% throttle range, fixed injector geometry, and a 28.86 mm throat [2, pp. 3–16]. The CDR fuel label does not match the test campaign; all records in this report are LOX/IPA.

The primary data are the eight AEL HDF5 records [1]. The records contain 100 channels sampled at 10 kHz. Chamber pressure PTX103 and load response LC190 use a -2.5 to -1.5 s baseline. Manifold-to-chamber pressure difference is calculated directly from stored gauge-pressure channels. Cross-test response metrics use a 20 ms moving average; Test 8 steady statistics use the fixed 4.0–12.5 s window. The reported ± values are time standard deviations.

Figure color convention. Blue denotes chamber pressure, red denotes load-cell response, green denotes LOX, orange denotes IPA, and violet denotes measured O/F. Solid lines are measured signals, dashed lines are commands or targets, and vertical dashed lines mark T0.

2 CAMPAIGN MATRIX AND SEQUENCE

Table 1: Commanded conditions, common-window measurements, and direct campaign outcome.

Test	Cmd. LOX/IPA [kg/s]	Cmd. O/F	Dur. [s]	Meas. LOX/IPA [kg/s]	Meas. O/F	Pc peak [bar]	Direct outcome
1	0.35/0.35	1.00	2.0	0.849/0.007	–	2.41	Stand configuration error; weak flame; no diamond
2	0.35/0.35	1.00	2.0	0.340/0.349	0.97	0.04	No visible flame
3	0.35/0.35	1.00	2.0	0.365/0.322	1.11	0.06	No visible flame
4	0.35/0.35	1.00	2.5	0.418/0.349	1.20	0.18	No visible flame
5	0.35/0.35	1.00	2.5	0.417/0.350	1.19	1.71	No visible flame; transient pressure response
6	0.30/0.22	1.36	2.5	0.297/0.225	1.32	4.29	No visible flame; stronger pressure response
7	0.42/0.28	1.50	3.0	0.423/0.280	1.51	9.52	Short burn with flame and Mach diamonds
8	0.45/0.25	1.80	13.0	0.450/0.250	1.80	14.37	Sustained burn and steady state

2.1 Cross-Test Ignition Timing

The spark and igniter command windows changed little across the campaign. The useful comparison is therefore the sequence from main-flow target issuance to measured flow formation and the first sustained chamber-pressure response.

Table 2: Cross-test ignition timing relative to stored T0. Measured-flow onset is the first sustained 10% flow threshold; Pc response is the first 20 ms sustained rise above 0.2 bar.

	Main-flow target start [s]		Measured 10% flow onset [s]		
Test	LOX	IPA	LOX	IPA	Pc response [s]
1	0.00	-0.30	0.24	–	0.84
2	0.07	-0.23	0.25	0.00	–
3	0.10	0.07	0.29	0.12	–
4	0.15	0.07	0.35	0.13	–
5	0.15	0.07	0.35	0.13	0.59
6	0.08	0.15	0.27	0.14	0.52
7	0.08	0.15	0.22	0.14	0.39
8	0.08	0.15	0.22	0.14	0.29

Common command schedule. Spark was commanded from -1.30 to -0.70 s in all tests. Igniter O_2/H_2 was commanded from -1.00 to 1.00 s in Tests 1–7 and extended to 2.00 s in Test 8. A dash denotes no detected threshold crossing.

Test 1 is not a valid flow-to-ignition comparison because the stand configuration prevented IPA flow formation. Tests 2–4 formed both propellant flows without a sustained chamber-pressure response. A repeatable Pc response first appeared in Test 5 and then advanced from 0.59 s to 0.52 s, 0.39 s, and 0.29 s through Tests 6–8. This progression, rather than the nearly unchanged command windows, is the principal ignition-sequence result.

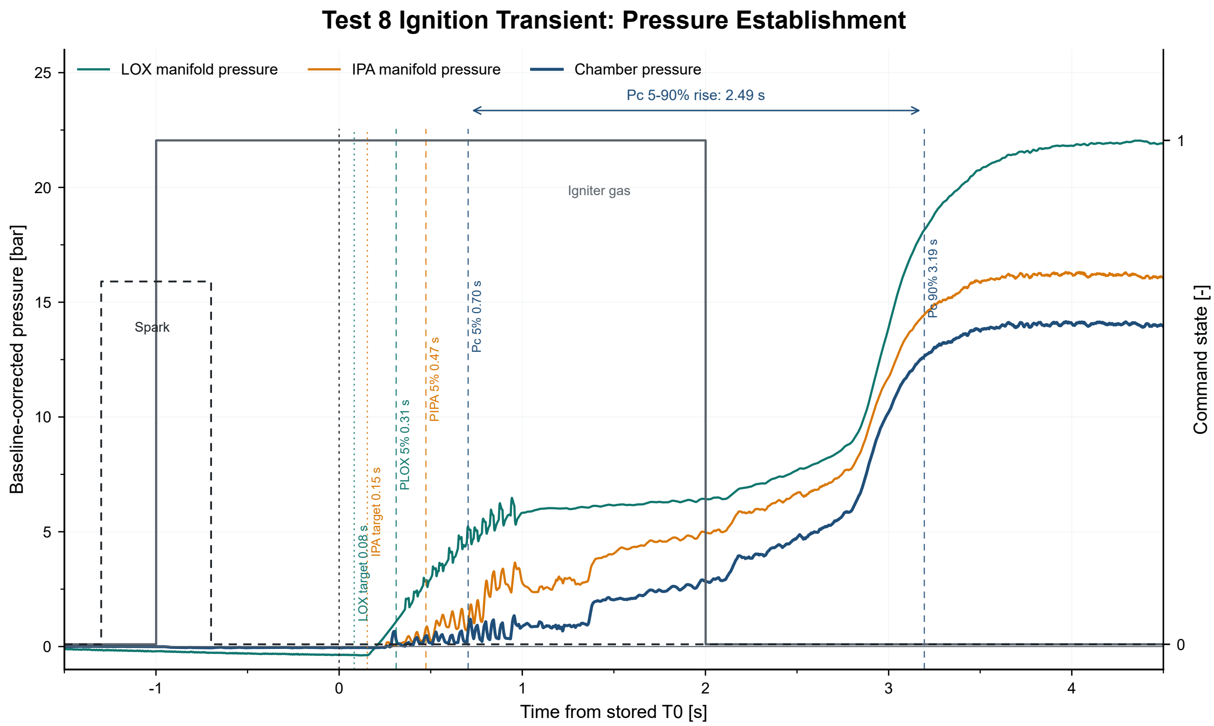

Figure 1: Test 8 ignition transient with baseline-corrected LOX-manifold, IPA-manifold, and chamber pressure. The combined igniter-gas command uses the binary 0–1 right-hand axis; the Spark trace is vertically offset for separation. Vertical references mark main-flow target starts, the 5% pressure-rise time for each measured pressure, and the 90% chamber-pressure time; dedicated igniter O2/H2 pressure channels were not present in the campaign record.

3 TEST-BY-TEST CAMPAIGN RECORD

Table 3: Configuration change, observation, measured response, and resulting campaign step.

Test	Recorded configuration	Direct observation	Data-derived result	Following campaign step
1	0.35/0.35 kg/s, O/F 1.00, 2.0 s	Stand configuration error identified on site; weak flame only	Pc peak 2.41 bar; IPA flow did not form; measured O/F invalid	Stand configuration corrected; repeat at O/F 1.00
2	Same flow point; IPA delay -0.3 s; 0.7 s ramps	No visible flame	Both flows formed; Pc peak 0.04 bar	IPA delay set to 0.0 s; LOX ramp increased to 1.0 s
3	Same flow point; zero IPA delay; 1.0 s LOX ramp	No visible flame	Measured O/F 1.11; Pc peak 0.06 bar	LOX ramp increased to 1.5 s; duration increased to 2.5 s
4	1.5 s LOX ramp; 2.5 s duration	No visible flame	Measured O/F 1.20; Pc peak 0.18 bar	Repeat the recorded principal template at Test 5
5	Same principal template as Test 4	No visible flame	Pc peak 1.71 bar; 1.03 s above 0.2 bar; load peak 101 N	Change to 0.30/0.22 kg/s, O/F 1.36, slower IPA ramp
6	0.30/0.22 kg/s, O/F 1.36, 2.5 s	No visible flame	Pc peak 4.29 bar; 2.44 s above 0.2 bar; load peak 166 N	Increase to 0.42/0.28 kg/s, O/F 1.50, 3.0 s
7	0.42/0.28 kg/s, O/F 1.50, 3.0 s	Flame and Mach diamonds; short burn	Pc peak 9.52 bar; load peak 800 N; response ended with the commanded flow	Increase O/F to 1.80 and extend duration to 13 s
8	0.45/0.25 kg/s, O/F 1.80, 13.0 s	Sustained flame and steady burn	14.05 bar(g), 1194 N, O/F 1.80 over the steady window	Campaign objective achieved

The first four tests separated facility readiness from engine behavior. Test 1 was dominated by the stand configuration error. After correction, Tests 2–4 delivered both propellants yet generated no chamber-pressure rise. Those results placed the ignition problem downstream of bulk flow delivery: main-flow timing, atomization, impingement, and mixing controlled the igniter-to-chamber handoff.

Tests 5 and 6 marked a transition from no pressure response to repeatable pressure buildup. The chamber reached 1.71 bar in Test 5 and 4.29 bar in Test 6, but neither test produced visible flame. These events were weak or spatially limited reactions coupled to the feed and stand, not stable engine operation. Test 7 was the first condition to produce a coherent exhaust structure. Test 8 then extended that operating region to a full-duration burn.

4 CROSS-TEST PRESSURE AND LOAD RESPONSE

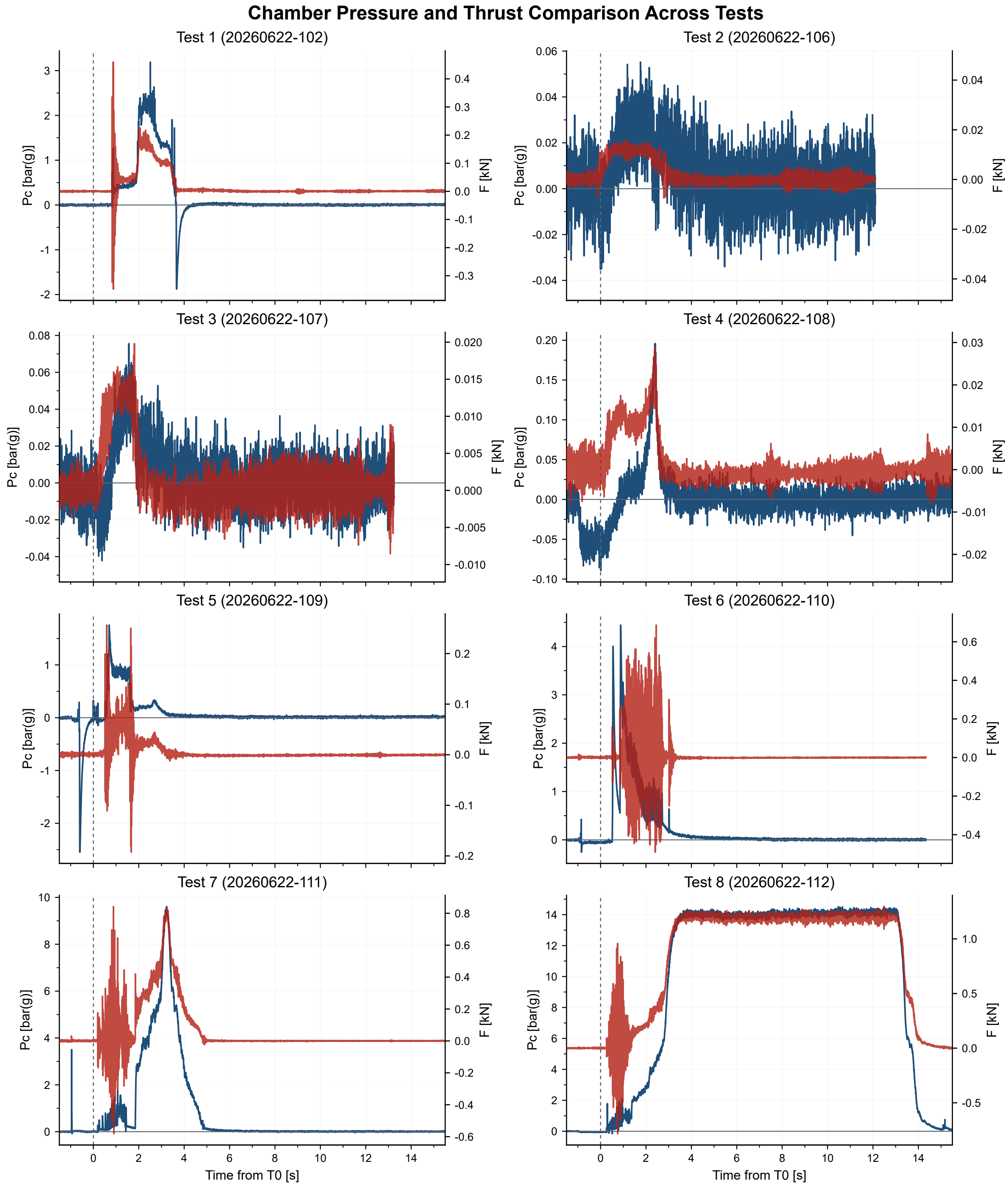

Figure 2: Chamber pressure and load-cell response for Tests 1–8 on identical time windows. Display traces are block-averaged; reported response metrics use the 20 ms moving average.

Tests 2–4 remained at the instrument-noise level despite established mass flow. Test 5 produced a short pressure rise, Test 6 produced a larger and longer response, and Test 7 approached the later Test 8 operating regime only at the end of its commanded duration. The load-cell oscillation is much larger than the corresponding chamber-pressure fluctuation during startup, identifying the stand/load path as the dominant source of the high-amplitude ringing.

5 TEST 7 AND TEST 8 IGNITION DEVELOPMENT

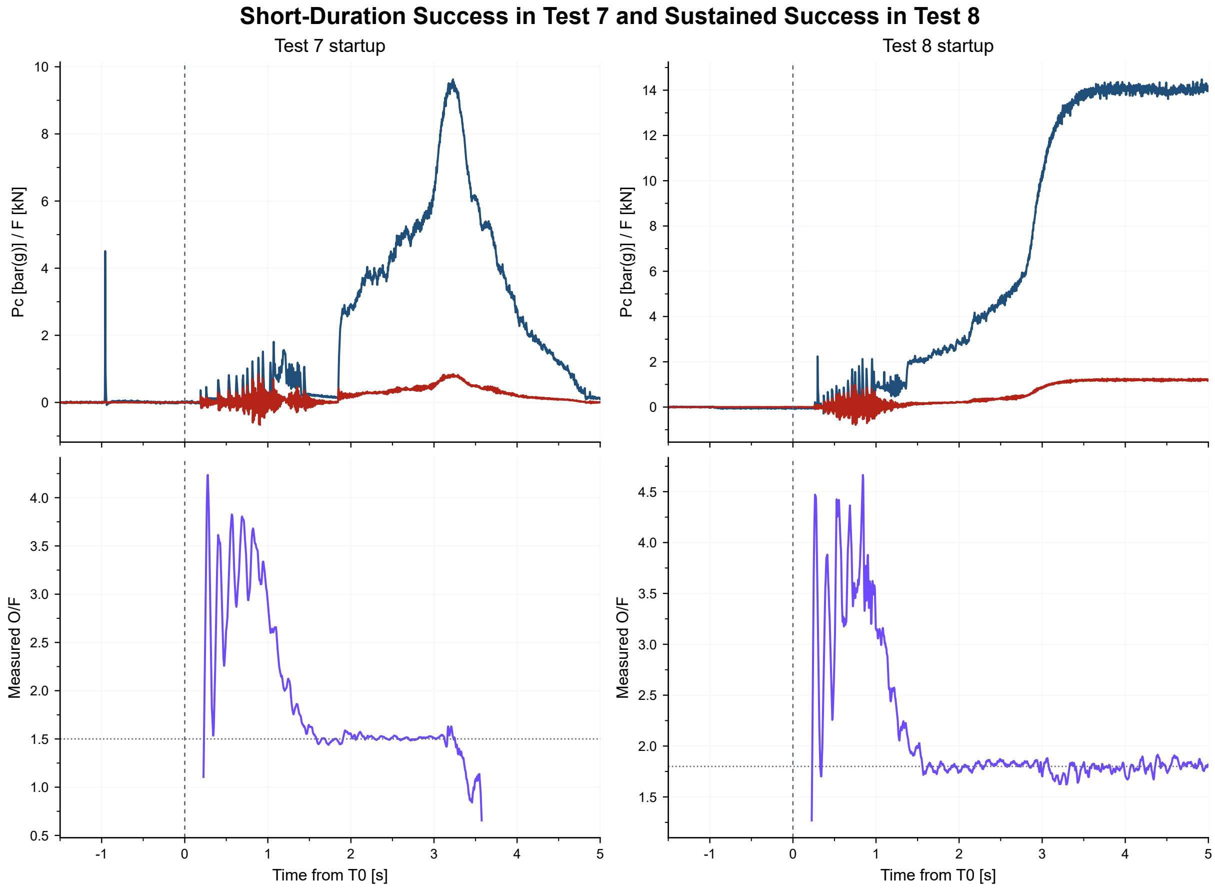

Figure 3: Startup pressure/load response and measured O/F for Test 7 and Test 8. O/F is calculated only after both measured flows exceed the validity threshold.

5.1 Test 7: short-duration success

Test 7 used 0.42/0.28 kg/s at commanded O/F 1.50 for 3.0 s. The exhaust showed a visible flame and Mach diamonds. Chamber pressure peaked at 9.52 bar and the load response peaked at 800 N. The main pressure rise occurred late and continued through flow termination, so the test demonstrated ignition and nozzle operation but did not contain a sustained performance window.

5.2 Test 8: sustained ignition

Test 8 used 0.45/0.25 kg/s at commanded O/F 1.80 for 13.0 s. Spark operated from -1.299 to -0.699 s and igniter O2/H2 from -0.999 to 2.001 s. Chamber pressure first exceeded 5% of the final level at 0.704 s and reached 90% at 3.195 s [3]. The engine then maintained the commanded flow point until shutdown.

6 TEST 8 STEADY-STATE PERFORMANCE

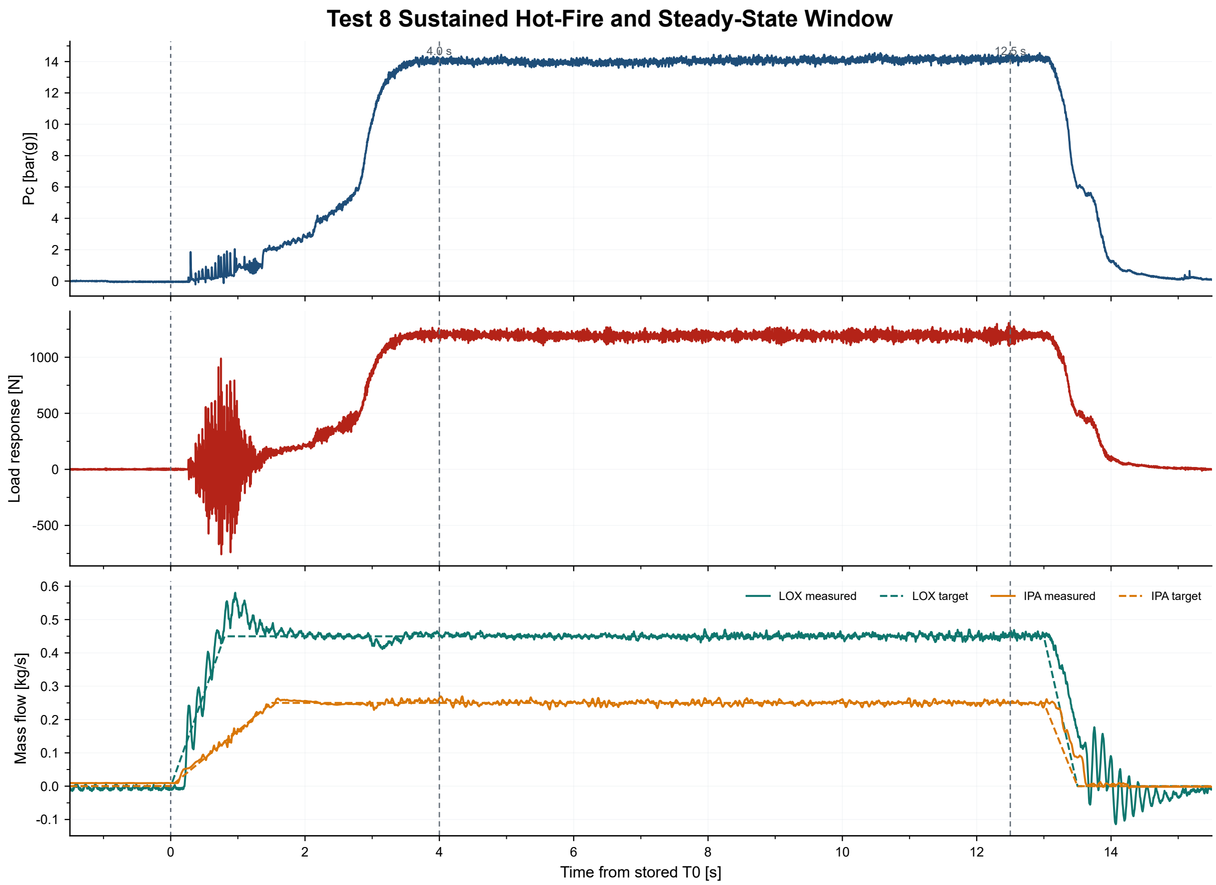

Figure 4: Test 8 sustained hot-fire response. Vertical boundary lines at 4.0 and 12.5 s delimit the fixed steady-state evaluation window.

Table 4: Test 8 steady-state performance. Each ± value is the time standard deviation over 4.0–12.5 s.

Pc [bar(g)]	Load [N]	LOX [kg/s]	IPA [kg/s]	O/F	Effective Isp [s]
14.05±0.18	1194±33	0.450	0.250	1.80	173.8

The stable chamber pressure was close to the 15 bar design point and the mean load approached the 1300 N design target. Both measured flows matched their commands. The remaining performance gap was concentrated in startup and injector hydraulic margin rather than steady mass-flow regulation.

7 MASS-FLOW AND MIXTURE-RATIO EVOLUTION

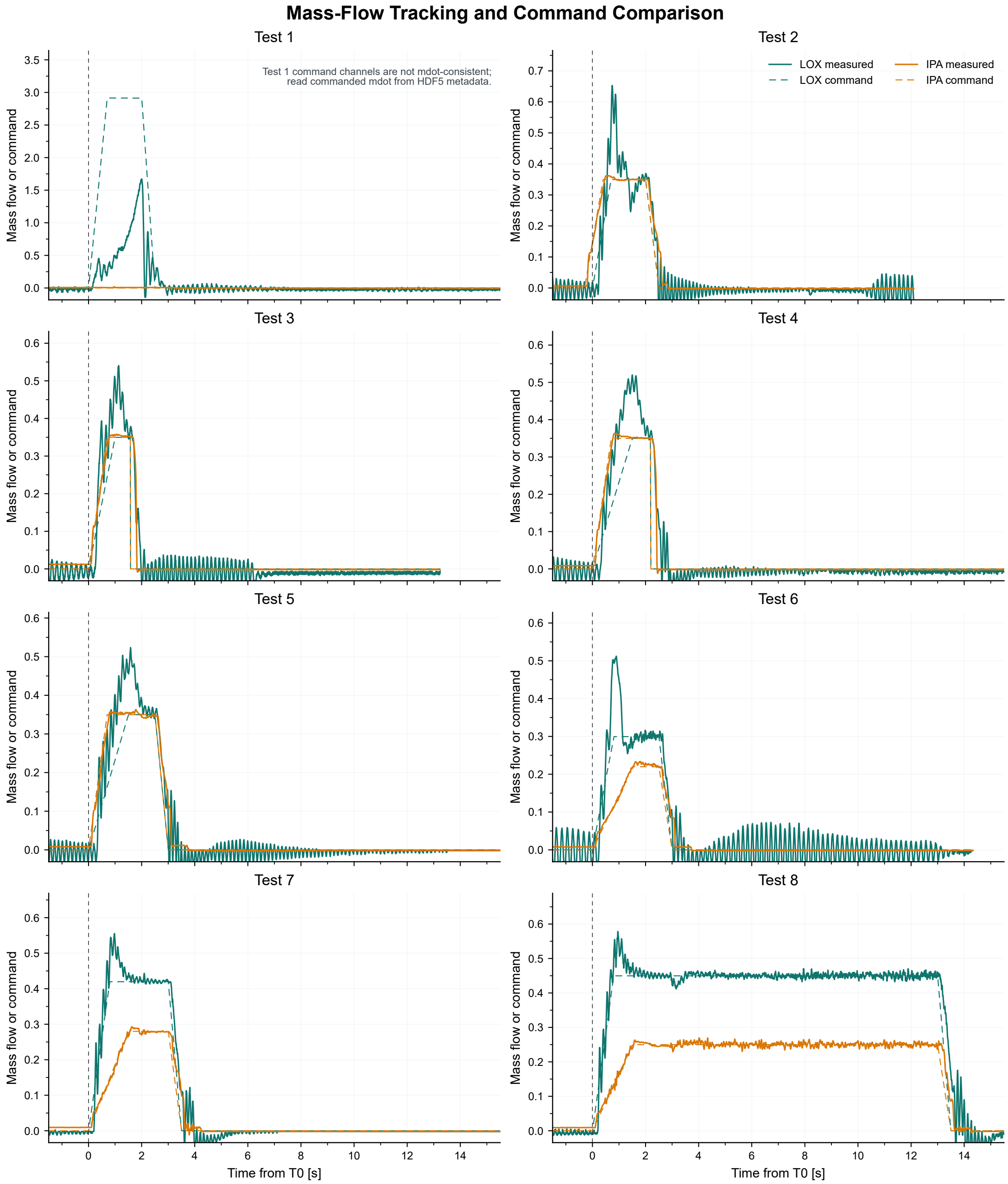

Figure 5: Commanded and measured LOX/IPA mass flow. Each panel uses an independent y-axis; its 99.5th-percentile maximum fills approximately 80% of the plotting height. Test 1 reflects the stand configuration error.

Tests 2–5 retained an O/F 1.00 command while timing and duration changed. Their measured late-hold O/F values were 0.97, 1.11, 1.20, and 1.19. Test 6 moved to O/F 1.36 and formed a stronger pressure response. Test 7 settled at O/F 1.51 and achieved the first clean short burn. Test 8 settled at O/F 1.80 and completed the sustained firing.

The AEL stand regulated mass flow in closed loop and met requested flow by raising upstream pressure even when injector resistance was too low; flow tracking confirmed delivery, not adequate jet velocity, atomization, impingement location, or igniter mixture.

8 INJECTOR PRESSURE-DROP AND SIZING ASSESSMENT

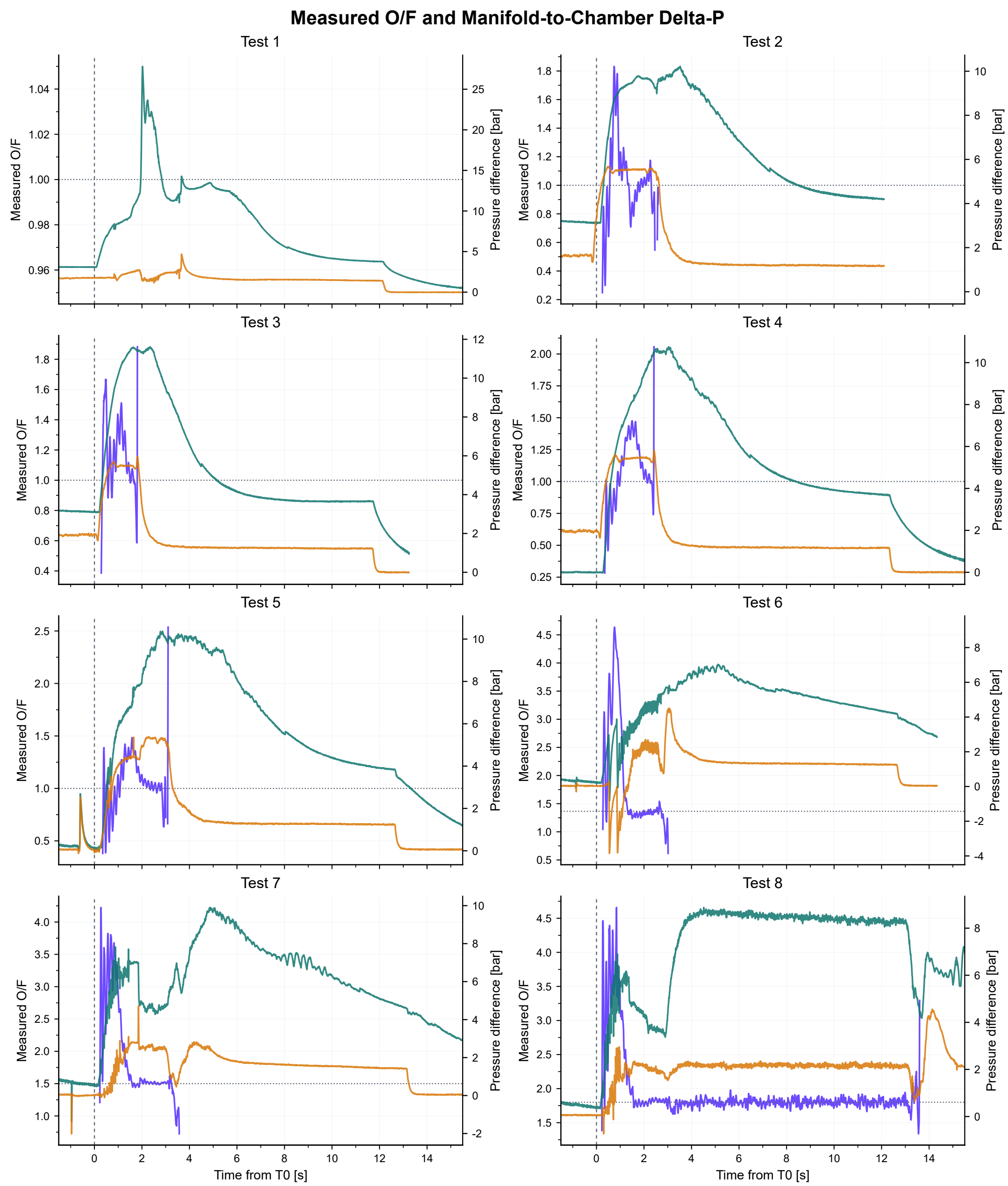

Figure 6: Measured O/F and manifold-to-chamber pressure difference for Tests 1–8. The pressure difference includes the line between each manifold sensor and the chamber and is therefore not an injector-only measurement.

The CDR correctly sized fixed injector area from the minimum-throttle pressure-drop requirement and checked the maximum point [2, pp. 8–11]. The released calculation reversed that logic and applied the minimum limit at maximum operation, producing oversized orifices and low hydraulic resistance.

At Test 8 steady state, the LOX and IPA manifold-to-chamber pressure differences were 8.47 and 2.17 bar at 14.05 bar(g) chamber pressure. Fuel-side pressure difference was only 15% of chamber pressure, half of the CDR criterion. This shifted relative jet momentum and the impingement field.

The oversized injector weakened atomization and increased sensitivity to arrival timing and transient O/F throughout Tests 2–6. Tests 7–8 overcame that weakness with a more favorable flow split, higher O/F, and longer mixture-formation time; the sizing defect remained.

9 TEST 8 STARTUP INSTABILITY

The Test 8 startup contained five stages: flow formation (0–0.25 s), intermittent flash (0.25–1.30 s), weak combustion (1.30–2.20 s), transition (2.20–3.30 s), and steady operation after 4.0 s [3]. LOX developed faster than IPA, driving the flash interval to mean O/F 3.26 before the mixture settled near 1.80. That oxidizer-rich interval produced repeated flashes rather than immediate chamber-wide combustion.

Table 5: Test 8 startup phases and dominant response.

Phase	Window [s]	Mean Pc [bar]	Mean load [N]	Engineering interpretation
Flow formation	0.00–0.25	-0.05	1	Propellant arrival without chamber-wide reaction
Intermittent flash	0.25–1.30	0.56	46	Oxidizer-rich local flashes; strong stand/load response
Weak combustion	1.30–2.20	2.41	180	Reaction established but below self-sustaining chamber state
Transition	2.20–3.30	7.35	609	Progressive flame spread and chamber-pressure buildup
Steady reference	4.00–12.50	14.05	1194	Sustained chamber-wide combustion

Table 6: Leading mechanisms for the ignition difficulty and startup instability.

Mechanism	Evidence	Engineering conclusion
Unequal LOX/IPA arrival	Test 8 flash O/F 3.26; LOX reached flow before IPA; O/F settled at 1.53 s	Primary driver of Test 8 flashing and slow handoff
Low injector pressure margin	Oversized orifices; Test 8 fuel-side difference 2.17 bar at 14.05 bar(g) Pc	Persistent loss of atomization and impingement control
Feed-system coupling	Flash pressure spectrum centered near 21.97 Hz	22 Hz pressure component represents a feed-system-coupled startup response
Stand/load structural response	Load spectrum repeatedly centered at 78–83 Hz; load ringing exceeded pressure oscillation	78–83 Hz response belongs primarily to the stand/load-cell structural path
Igniter handoff	Igniter flow ended at 2.00 s while chamber pressure was still below the final state	Main flow required additional time to establish chamber-wide combustion

Negative pressure and load peaks during the flash interval are sensor/stand dynamic response, not physical negative chamber pressure or negative engine thrust. The startup improvement path is direct: reduce the initial LOX lead, accelerate IPA formation, and restore injector pressure margin.

10 FINDINGS AND ENGINEERING LESSONS

1. The J1 stand configuration error controlled Test 1. After correction, the remaining ignition difficulty belonged to engine sequence and injector behavior.
2. Tests 2–4 proved that commanded mass flow was delivered without ignition. Facility flow control and injector spray quality were separate closures.
3. Tests 5–6 showed progressive pressure buildup but no visible flame. They were intermediate weak-reaction states, not successful firings.
4. Higher O/F, revised ramp timing, and longer duration moved the engine into a viable ignition region in Tests 7–8.
5. The injector sizing error reduced fuel-side pressure margin and weakened atomization and impingement control across the campaign.
6. Test 8 steady performance was strong; its remaining deficiency was a slow, oxidizer-rich startup coupled to the feed system and stand dynamics.

Future hot-fire work should size fixed geometry at minimum throttle, verify the maximum point, recalculate the released geometry, compare it with as-built inspection, change one startup variable at a time, synchronize video and DAQ, instrument pressure immediately upstream of each injector circuit, and characterize the thrust stand dynamically.

11 CONCLUSION

The Kimchi Engine completed sustained LOX/IPA operation at 0.45/0.25 kg/s and O/F 1.80. Test 7 established the viable ignition region; Test 8 extended it to a stable 13 s burn. Oversized injector orifices reduced pressure margin and ignition robustness, while unequal LOX/IPA buildup produced an oxidizer-rich startup. Future hardware must correct the injector sizing rule so the engine reaches the same result without a long flashing transition.

12 REFERENCES AND REPRODUCIBILITY

[1] Airborne Engineering Ltd. and Kimchi Engine Team. J1 kimchi engine test records 20260622-102, -106 through -112. HDF5 data archive, 2026. Recorded 22 June 2026; read-only analysis copies.

[2] Kimchi Engine Team. Kimchi engine critical design review. Internal design review, Race2Space 2026, 2026.

[3] Kimchi Engine Team. Startup and combustion-instability analysis of record 20260622-112. Internal data analysis, Race2Space 2026, 2026.

12.1 Key data channels

Channel	Analysis role	Stored unit
PTX103	Chamber pressure	bar(g)
PTX101 / PTX102	LOX / IPA manifold pressure	bar(g)
LC190	Axial load-cell and stand response	N
M801 / M730	Measured LOX / IPA mass flow	kg/s
DAU1094_mdot_req / DAU1095_mdot_req	Closed-loop mass-flow target	kg/s
V893 / V891 / V291	Spark / igniter O2 / igniter H2 command	counts
V824 / V730	Main LOX / IPA run-valve state	counts
V823 / XT823	LOX throttle command / feedback	mm
V731 / XT731	IPA throttle command / feedback	turns

The complete per-test channel dictionary, source hashes, event timing, processing manifest, campaign metrics, and decision log are delivered with the LaTeX source. Historical items that do not affect the technical conclusions remain in `OPEN_ITEMS.md` rather than in the report body.