ENGINEERING ANALYSIS · INFINITY TURBINE LLC · YUKON PLACER GOLD APPLICATION · NOVEMBER 2026

Log-Boiler-Fired Transcritical CO_2 Cylinder Expander for Hydraulic Power — Optimum Heat Source & 800 °C Case

This follows on from the 100 °C / 15 °C study. Cooling is now 5 °C (41 °F) creek or glycol water, and the heat comes from a 500,000 BTU/h log boiler whose flue gas reaches 800 °C (1,472 °F). The CO_2 cylinders drive hydraulic plungers that power the wash plant directly.

39.2 kW
Net hydraulic power, 800 °C case · 52.6 hp

50.7 kW
Gross hydraulic power · 68 hp

147 L/min
Oil at 207 bar · 38.8 gpm at 3,000 psi

26.8 %
Wood → net hydraulic (was 3.6 % at 100 °C / 15 °C)

01 Answer in brief

What is the optimum heat source? A log boiler already burns at well over 800 °C. The best choice is therefore to **put the CO_2 heater coil directly in the flue gas**, not to heat water or thermal oil first. Every intermediate loop caps the CO_2 temperature, and in this cycle each extra 100 °C of CO_2 inlet temperature adds about 2–8 kW of net hydraulic power, with the largest gains at the low end (Section 03).

How hot should the CO_2 be? On thermodynamics alone, as hot as possible. In practice the gains shrink above about 500 °C while cost and risk climb steeply: nickel-alloy heater tubes, 300 bar design, and piston rings and valves running far above the temperatures used in steam engines. The recommended engineering optimum is **CO_2 at 450–550 °C and 200–250 bar, heated directly by flue gas**. That gives about **32–35 kW (43–47 hp) net hydraulic**, compared with 39 kW at the 700 °C limit.

The full 800 °C case: with CO_2 heated to 700 °C at 300 bar (a 100 K approach to the 800 °C flue gas), the system delivers **50.7 kW gross and 39.2 kW net hydraulic power**. That is 147 L/min (38.8 gpm) of oil at 207 bar (3,000 psi), about **7 times the 100 °C system's output** from the same wood.

Performance from 500,000 BTU/h of wood (146.5 kW)

Case	Net hydraulic	Wood → net
Previous study: 100 °C water, 15 °C cooling	5.3 kW · 7.2 hp	3.6 %
100 °C water, **5 °C cooling**	6.9 kW · 9.3 hp	4.7 %
Thermal oil 320 °C → CO_2 300 °C, 200 bar	22.4 kW · 30 hp	15.3 %
Recommended: direct-fired, CO_2 500 °C, 200 bar	**32.2 kW · 43 hp**	**22.0 %**
800 °C flue: CO_2 700 °C, 300 bar	**39.2 kW · 52.6 hp**	**26.8 %**

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Net = hydraulic output after the CO_2 feed pump is driven by a hydraulic motor taken from the same output. Assumptions are listed in Section 09.

02 Effect of 5 °C cooling and the Yukon setting

With 5 °C (41 °F) cooling water and a 5 K approach, CO_2 condenses at **10 °C and 45.0 bar (50 °F, 653 psia)**, compared with 20 °C and 57.3 bar before. The lower back pressure raises the expander pressure ratio and cuts pump work per kilogram. At the original 100 °C source this alone lifts net output by about 30 % (5.3 → 6.9 kW). The colder sink matters even more once the CO_2 is hot: at 700 °C the cylinders expand across a 6.4 : 1 pressure ratio.

Season and cooling source. Yukon placer mining runs mainly May to September, when air can reach 25–30 °C (77–86 °F). In summer, **5 °C cooling therefore has to come from creek water or groundwater** (typically 2–8 °C) through a plate heat exchanger, with a closed glycol loop on the CO_2 condenser side so the condenser never sees silt or freezing. A glycol dry cooler covers shoulder seasons and winter operation, down to −40 °C ambient.

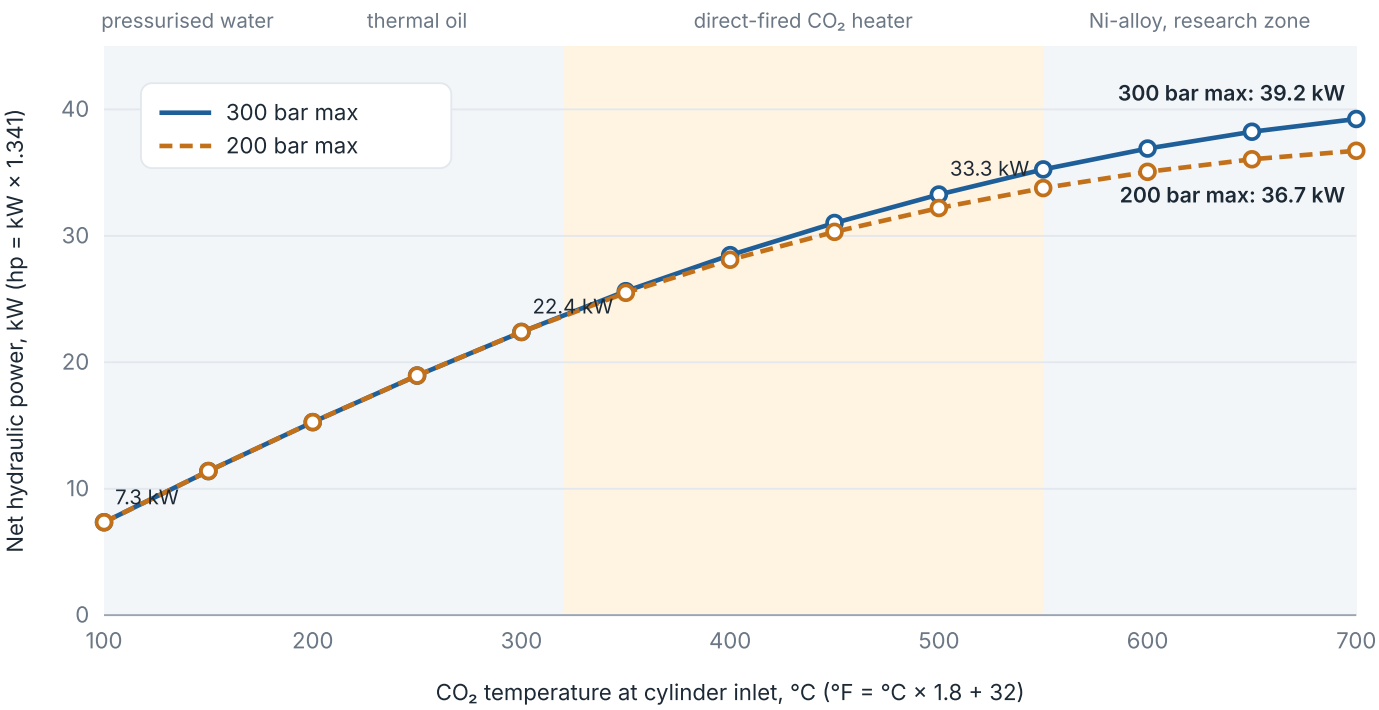
Cold-climate design points

- Hold condensing at 8–10 °C with a 3-way glycol valve. Do not let CO_2 condense colder in winter: pump suction head and liquid density change, and the triple point is −56.6 °C (−70 °F).
- Standstill pressure: stopped at −30 °C, the CO_2 sits at about 14 bar as liquid. On a 25 °C summer day it reaches about 64 bar, and above 31 °C it becomes supercritical. Design the low side for 90 bar, or fit a small standstill chiller.
- Heated hydraulic reservoir and oil cooler on the same glycol loop. Use low-pour-point hydraulic oil (ISO VG 32 arctic grade) for −40 °C cold starts.
- Air preheater (HX-104) protects against cold combustion air and recovers 53 kW (182,000 BTU/h) of flue heat.

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03 Choosing the heat source

For each heat-transfer arrangement, the CO_2 high pressure is optimised (capped at 200 or 300 bar), the recuperator is pinch-limited (10 K), and the boiler efficiency is calculated from the flue-gas temperature that the heater can actually reach. The flue enters at 800 °C, and an air preheater takes the stack down to 150 °C.



Net hydraulic power versus CO_2 cylinder-inlet temperature from 500,000 BTU/h of wood, with 5 °C cooling. Shaded bands show which heat-transfer method can reach each temperature. Gains fall from about 3.8 kW per 50 °C below 300 °C to about 1 kW per 50 °C above 600 °C.

Heat source arrangement	CO_2 in °C / °F	High side bar / psia	Boiler η (wood → CO_2)	Cycle η	Gross hyd. kW / hp	CO_2 pump kW	Net hyd. kW / hp	Wood → net
Pressurised hot water, 100 °C loop	95 / 203	100 / 1,450	78 %	6.1 %	12.1 / 16	4.4	6.9 / 9.3	4.7 %
Pressurised hot water, 180 °C loop (~15 bar)	175 / 347	140 / 2,030	78 %	11.7 %	21.3 / 29	6.7	13.4 / 18	9.1 %
Thermal oil, 320 °C loop	300 / 572	200 / 2,900	78 %	19.6 %	33.4 / 45	9.3	22.4 / 30	15.3 %
Direct-fired CO_2 heater (recommended)	**500 / 932**	**200 / 2,900**	**76 %**	**28.8 %**	**41.5 / 56**	**7.9**	**32.2 / 43**	**22.0 %**
Direct-fired, 800 °C flue, 200 bar cap	700 / 1,292	200 / 2,900	71 %	35.5 %	44.5 / 60	6.6	36.7 / 49	25.1 %
Direct-fired, 800 °C flue, 300 bar	**700 / 1,292**	**300 / 4,350**	**72 %**	**37.4 %**	**50.7 / 68**	**9.8**	**39.2 / 53**	**26.8 %**

Why direct-firing wins

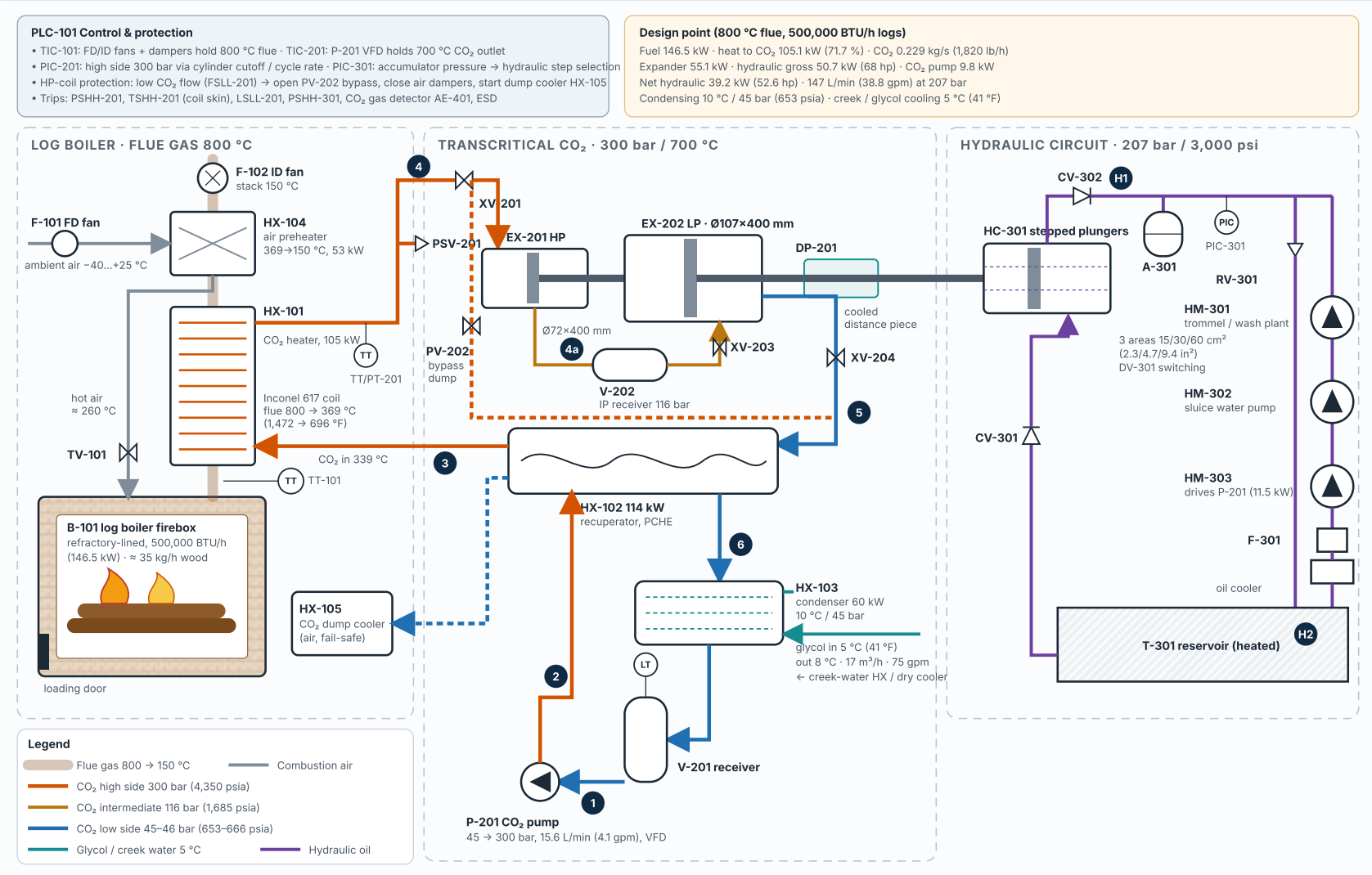
Water above 180 °C needs heavy pressure vessels. Thermal oil is limited to about 320–340 °C and degrades if it overheats in a wood firebox. Neither can use the 800 °C the fire provides. A CO_2 coil in the flue gas avoids a whole heat-transfer step and its temperature loss, and CO_2 is a stable, non-flammable heat carrier. As the CO_2 gets hotter, boiler efficiency falls slightly (78 → 72 %) because the gas leaving the coil is hotter. The air preheater recovers most of that.

Why stop at 450–550 °C in practice

Up to about 550 °C the CO_2 heater can be stainless 347H or 800H tube and the cylinders can follow superheated-steam-engine practice: cast steel, graphite or carbon piston rings, and Stellite-faced poppet valves. Going to 700 °C means Inconel 617/740H tubing, ceramic or carbon rings, and 300 bar at temperatures where creep governs. All that buys only +7 kW (+22 %). For a remote Yukon site, reliability and field repair matter more than the last few kW.

04 P&ID — direct-fired 800 °C configuration

Log boiler with an in-flue CO_2 heater and air preheater; compound (HP + LP) CO_2 cylinders in tandem with stepped hydraulic plungers; recuperator; creek-water/glycol condenser; and the hydraulic power circuit feeding the wash plant.

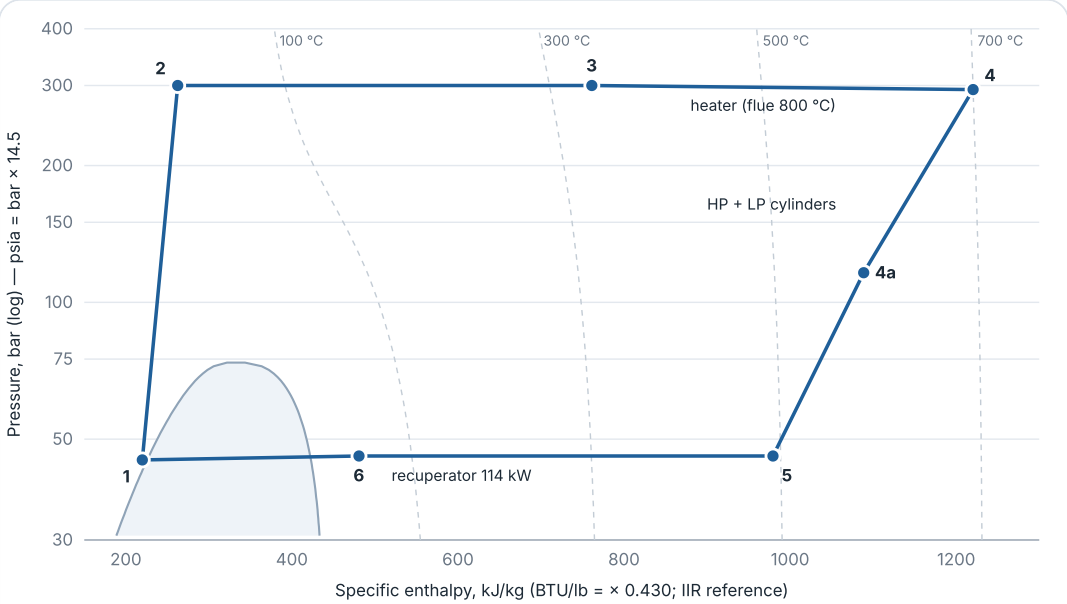


P&ID tags: B boiler, F fan, HX heat exchanger, EX expander cylinder, HC hydraulic plunger chamber, DP distance piece, V vessel, P pump, XV/PV/TV on-off, pressure and temperature control valves, PSV/RV safety and relief valves, CV check valve, HM hydraulic motor, A accumulator, T tank. Stream numbers refer to Section 05.

05 800 °C design point — states, flows and pressures

CO_2 heated to 700 °C at 300 bar; condensing at 10 °C. CO_2 flow 0.229 kg/s (1,820 lb/h). Two-stage expansion with an intermediate receiver at 116 bar. Enthalpy reference IIR.

#	Location	Pressure bar / psia	Temperature °C / °F	Enthalpy kJ/kg / BTU/lb	Density kg/m³ / lb/ft³	Phase
1	Pump suction (receiver)	45.0 / 653	8 / 46	220 / 95	879 / 54.85	subcooled liquid
2	Pump discharge	300.0 / 4,351	36 / 97	263 / 113	925 / 57.74	compressed liquid
3	Recuperator cold out / heater in	300.0 / 4,351	339 / 642	761 / 327	260 / 16.22	supercritical
4	Heater out / HP admission	294.0 / 4,264	700 / 1292	1220 / 525	150 / 9.34	supercritical
4a	HP exhaust / LP admission (V-202)	116.2 / 1,685	589 / 1091	1089 / 468	70 / 4.37	supercritical
5	LP cylinder exhaust	45.9 / 666	492 / 918	979 / 421	32 / 1.98	superheated vapour
6	Recuperator hot out / condenser in	45.9 / 666	46 / 115	481 / 207	96 / 6.01	superheated vapour



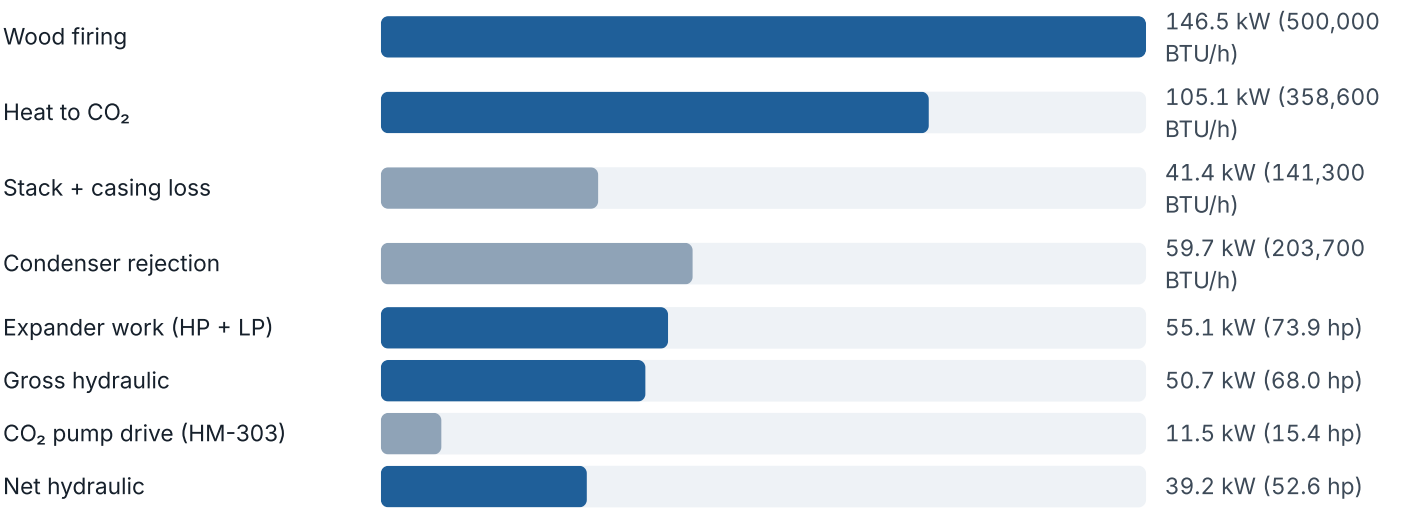
CO_2 pressure–enthalpy diagram, 800 °C case: 1→2 pump, 2→3 recuperator, 3→4 flue-gas heater, 4→4a HP cylinder, 4a→5 LP cylinder, 5→6 recuperator, 6→1 condenser.

Stream / duty	Metric	Imperial
Wood firing	146.5 kW · ≈ 35 kg/h	500,000 BTU/h · ≈ 77 lb/h
Flue gas 800 → 369 °C (HX-101)	0.21 kg/s	1,680 lb/h · 1,472 → 696 °F
Heat to CO_2 (HX-101)	105.1 kW	358,600 BTU/h
Air preheater (HX-104), flue 369 → 150 °C	53.4 kW	182,200 BTU/h
CO_2 mass flow	0.229 kg/s · 824 kg/h	1,820 lb/h
Liquid CO_2 to pump	15.6 L/min	4.1 gpm
CO_2 at HP admission (4)	1.53 L/s	3.2 ft³/min
CO_2 at LP exhaust (5)	7.23 L/s	15.3 ft³/min
Recuperator (HX-102)	114.1 kW	389,300 BTU/h
Condenser (HX-103)	59.7 kW	203,700 BTU/h
Glycol/creek water 5 → 8 °C	≈ 17 m³/h	≈ 75 gpm · 41 → 46 °F

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Hydraulic oil at 207 bar	147 L/min	38.8 gpm at 3,000 psi
...or at 350 bar	87 L/min	23.0 gpm at 5,000 psi

Power balance



Energy check: 105.1 kW heat + 9.8 kW pump = 55.1 kW expander + 59.7 kW condenser. Cycle efficiency 37.4 %; wood-to-net hydraulic 26.8 %. Fans and glycol pump (≈ 2–3 kW) come on top. They can be hydraulically driven from the output, or run from a small battery/solar bank.

06 Expander and hydraulic coupling

At 700 °C / 300 bar the CO_2 expands across a **4.7 : 1 volume ratio**. A single cylinder would need about 20 % cutoff, and the rod force would fall about 5 : 1 over the stroke, which is a poor match for a fixed-area hydraulic plunger. The design therefore uses **compound expansion**, as in a steam engine. A high-pressure cylinder expands 294 → 116 bar into the intermediate receiver V-202, and a low-pressure cylinder expands 116 → 46 bar. Each stage has a pressure ratio of about 2.5, and both pistons sit on one rod with the hydraulic plungers.

Over a stroke the combined force still varies about 2 : 1. A three-area stepped plunger (15 / 30 / 60 cm², switched by digital valves DV-301) keeps the CO_2 force matched to the 207 bar accumulator to within about ±15 %.

Free-piston tandem units (base design)

Item	800 °C case	500 °C case
Tandem units	2, double-acting, 180° phased	2
HP cylinder bore × stroke	Ø72 × 400 mm · 2.8 × 15.75 in	Ø82 × 400 mm
LP cylinder bore × stroke	Ø107 × 400 mm · 4.2 × 15.75 in	Ø111 × 400 mm
Intermediate pressure	116 bar · 1,685 psia	95 bar · 1,376 psia
Cycle rate / piston speed	30 cpm · 0.40 m/s (79 ft/min)	30 cpm
Peak rod force per unit	136 kN · 30,600 lbf	100 kN · 22,600 lbf
Mean rod force per unit	69 kN · 15,500 lbf	56 kN · 12,700 lbf
Plunger area, mean / max	30.6 / 60.5 cm² · 4.7 / 9.4 in²	25 / 45 cm²
Oil at 207 bar	147 L/min · 38.8 gpm	120 L/min · 31.8 gpm

> **Alternative: crank engine driving a hydraulic pump.** A compound engine with a crank and flywheel at about 400 rpm (HP Ø56 mm, LP Ø83 mm, 100 mm stroke; peak gas loads 44 / 38 kN) can drive a variable-displacement axial-piston pump. The rotating mass smooths the force variation without digital hydraulics, and the parts are smaller. The cost is a crankcase, crossheads and a lubricated running gear kept away from the hot cylinders.

Hot-end engineering at 700 °C

- **Cylinders and heads:** Inconel 718/625 liners and heads. Insulated outside, so heat leaks into the cylinder wall are not lost.
- **Rings:** oil cannot be used. Options are carbon-graphite or silicon-nitride rings, or a labyrinth/clearance-seal piston. Expect blow-by of 2–5 %, which is in the efficiency assumption.
- **Valves:** Nimonic/Stellite poppet valves (exhaust-valve practice from diesel engines), hydraulically actuated from the PLC.
- **Distance piece DP-201:** a long, glycol-cooled rod section so the hydraulic chambers and seals stay below 60 °C (140 °F).
- **At 500 °C** each of these becomes ordinary superheated-steam practice. This is the main reason for the recommended optimum.

07 Site operation: wood, loads and control

- **Wood use:** 146.5 kW of firing is about 35 kg/h (77 lb/h) of seasoned spruce or pine at 20 % moisture. That is ≈ 0.84 t (1,850 lb) per 24 h, roughly 0.8 cord per day. A log boiler with a 1–1.5 m³ firebox needs reloading every 3–5 h.

- **What 39–52 hp of hydraulic power runs:** a small placer wash plant's trommel drive, feed and stacker conveyors and shaker deck (typically 20–50 hp combined). Large sluice water pumps (often 100–300 hp) are beyond it unless water is gravity-fed.
- **Batch firing:** log boilers cycle through each burn. Hold the 800 °C flue temperature at HX-101 with primary/secondary air dampers and flue-gas recirculation. The hydraulic accumulator, plus a small thermal store, rides through refuelling dips.

> **The critical safety case: the fire cannot be switched off.** If CO_2 flow stops (pump trip, valve fault), the HX-101 coil will overheat within minutes in 800 °C gas. Required protection: low-flow trip FSLL-201 that opens bypass PV-202 so CO_2 keeps circulating through the fail-safe air dump cooler HX-105; air dampers that close to starve the fire; coil skin thermocouples (TSHH-201); and a coil design that can survive a stagnant overheat to its relief-valve set pressure. Design to ASME BPVC Section I/VIII and B31.1 (or PED Category IV in the EU), with a CO_2 gas detector in any enclosure.

08 Conclusions

Fire the CO_2 directly; design for about 500 °C and 200–250 bar; 800 °C flue is the 39 kW ceiling

- Dropping the condenser to 5 °C (CO_2 condensing at 10 °C / 45 bar) adds about 30 % at the low-temperature end and is essential for the high-temperature cycle. In the Yukon summer it needs creek or groundwater cooling through a glycol loop.
- The optimum heat source for a log boiler is a **CO_2 heater coil in the flue gas**, not a hot-water or thermal-oil loop.
- From 500,000 BTU/h of wood: about **32 kW (43 hp) net at 500 °C / 200 bar**, rising to **39.2 kW (52.6 hp) net and 50.7 kW (68 hp) gross at 700 °C / 300 bar** with 800 °C flue gas. That is 147 L/min (38.8 gpm) of oil at 3,000 psi and 26.8 % wood-to-hydraulic efficiency.
- At these temperatures, compound HP/LP cylinders with stepped hydraulic plungers (or a crank-driven pump) are required. The 500 °C design point keeps the hot end within proven steam-engine materials. That makes it the best choice for a remote site.

09 Basis and assumptions

Parameter	Value used
Wood firing	500,000 BTU/h (146.5 kW) fuel input; 5 % casing/ash loss; flue gas 800 °C into the heater
Boiler model	Flue exits CO_2 heater at CO_2 inlet + 30 K; air preheater to 150 °C stack. Gives 71–78 % wood → CO_2
Cooling / condensing	5 °C water/glycol; CO_2 condensing 10 °C (45.0 bar); subcooled to 8 °C
Heater approach	Direct-fired: 100 K to 800 °C flue at the hot end. Water/oil loops: 5 K to loop supply
Recuperator	Counterflow, 10 K minimum pinch (checked along the full length)
Expander	80 % isentropic (indicated) per stage; piston → hydraulic transfer 92 %
CO_2 feed pump	65 % isentropic; driven by a hydraulic motor at 85 % (counted against the output)
Pressure losses	2 % in the heater and 2 % in the low-side path
High-side pressure	Optimised in 10 bar steps, capped at 200 or 300 bar
Properties	CoolProp 8 (Span–Wagner CO_2); flue-gas cp 1.15 kJ/kg·K; wood 4.2 kWh/kg at 20 % moisture

Preliminary feasibility analysis, not a certified design. High-temperature CO_2 heater, cylinder and pressure-relief design require detailed engineering to the applicable codes and Yukon regulatory requirements.

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