A Reduced-Order Huff-n-Puff Heat Extraction Model

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Keywords

huff-n-puff; reduced-order model; geothermal heat extraction; mechanical energy storage; cyclic injection-production; field calibration

ABSTRACT

Multiple repeatable injection-production cycles were operated at short time scales over multiple days at a grid-connected energy facility with mechanical energy storage capability in South Texas. The cycles were operated on an injection–hold–production schedule chosen to emulate a single-well geothermal heat-extraction duty, indicating that such huff-n-puff operations can be controlled and repeated in the field. Sustained operation over many cycles requires a periodic recharge strategy, in which a small amount of additional fluid is injected to balance the system. While the site's low geothermal gradient is not of power-production grade, the campaign produced a dense, high-quality pressure and flow-rate data set. This field record calibrates a nonlinear lumped-parameter hydromechanical reduced-order model (ROM) that reproduces the fully variable flow and pressure of the cycle, including the injection-production reversals that define huff-n-puff (cyclic) operations. This flow-and-pressure solver is coupled to a thermal reduced-order model that resolves heat transport for the imposed flow; together they form a field-calibrated hydromechanical ROM coupled to a thermal projection model for huff-n-puff heat extraction.

With the flow response anchored to these field measurements, the calibrated model is used to project heat extraction under representative geothermal conditions, examining produced-fluid temperature, thermal recovery, and depletion trends across repeated cycles. The approach retains the computational speed of the reduced-order solver, in minutes rather than the hours required by full-physics simulations, enabling rapid scenario screening, long-term depletion forecasting, and operational optimization of grid-responsive geothermal projects. Building on the field-validated mechanical energy storage platform demonstrated at an earlier pilot site (Simpkins et al., 2023) and multi-fracture huff-n-puff pressure performance (Rivas et al., 2025b), this work delivers a forward-looking assessment of how heat extraction via huff-n-puff would operate.

1. Introduction

The increasing penetration of variable renewable energy in modern electricity grids has created demand for flexible, firm generation capable of balancing supply and demand on timescales ranging from hours to days. Geothermal energy, in particular, heat extraction from hot dry rock (HDR) and Enhanced Geothermal Systems (EGS), offers a promising path to low-carbon firm power (Horne et al., 2025). The feasibility of this approach in crystalline rock was first demonstrated at Fenton Hill, New Mexico, where the Los Alamos National Laboratory team drilled into hot granite in the Jemez Mountains beginning in 1974 and achieved the world's first sustained heat extraction from an engineered fracture in impermeable HDR (Smith et al., 1975; Brown and Duchane, 1999; Brown et al., 2012).

A fundamental feature of geothermal power conversion is that production temperature is the primary economic lever: in Rankine and organic Rankine cycle (ORC) systems applicable to EGS, both cycle efficiency and the thermal enthalpy available for conversion increase with fluid temperature, making net power output a strongly nonlinear function of produced-fluid temperature. Operational strategies that sustain higher production temperatures over the project lifetime, or recover temperatures more completely between cycles, therefore carry direct economic leverage on project viability (Horne et al., 2025; Aljubran and Horne, 2024).

The classical approach to EGS relies on a doublet configuration: cold fluid is injected through one well, travels through the stimulated fracture network, acquires heat from the surrounding rock, and is produced from a second well. The central engineering challenge is achieving reliable hydraulic connectivity between the two wellbores at depth. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) achieved sustained inter-well circulation at commercial injection rates in granite near Milford, Utah, following years of stimulation and characterization campaigns (Moore et al., 2019; Xing et al., 2022), illustrating both the potential and the demanding engineering requirements of doublet EGS connectivity.

Huff-n-puff operations offer a complementary single-well approach that sidesteps the inter-well connectivity requirement: fluid is injected through a single well to pressure-charge the surrounding fractures, then produced back through the same well during discharge. This cyclic charging and discharging is well-suited to grid-responsive operation and does not require a second wellbore connected in the subsurface. The pressure response of the cycle (how the system charges, holds, and rebounds) governs how the operation is controlled; over many cycles the same process re-heats the returning fluid, the thermal recovery on which huff-n-puff heat extraction ultimately depends.

The huff-n-puff approach has clear geothermal precedent. The GeneSys Project in Germany (2003–2011) demonstrated single-well huff-n-puff heat production for district heating from a vertical well connected to a large hydraulic fracture, operating in cyclic injection-production mode on daily-to-weekly cycles (Orzol et al., 2005; Tischner et al., 2010, 2013), substantially longer than the sub-daily cycles of the present campaign. At Utah FORGE, cyclic single-well injection-flowback campaigns in granite, though designed for geomechanical characterization rather than heat extraction, showed clear pressure rebound after each flowback, the pressure analog of the thermal recovery that huff-n-puff heat extraction relies upon (Xing et al., 2022). On the mechanical energy storage side, Simpkins et al. (2023) field-validated the huff-n-puff operational framework in deep hydraulic fractures in South Texas, and Rivas et al. (2025b) extended it to multi-fracture configurations.

These efforts reflect an incremental development of a single underlying technology: mechanical energy storage and heat extraction are realized by the identical huff-n-puff operation, and the available temperature gradient sets the form of energy recovered. Where the gradient is below power-production grade, the cycle recovers the pressure work stored in the fracture system; where it is sufficient, the same cycle additionally extracts heat. A mechanical energy storage deployment is therefore both a capability in its own right and a field-learning platform for heat extraction, because the flow and pressure behavior that governs the cycle is common to both regimes. The present work builds on this platform using new field data from a grid-connected energy facility with mechanical energy storage capability, a separate instrumented surface facility distinct from the earlier pilot, in which repeatable injection-production cycles were operated on a geothermal-representative schedule and recorded at high fidelity.

Designing and operating huff-n-puff heat extraction requires models that simulate fracture heat transport under fully variable, reversing flow over many cycles. The classical Lauwerier–Gringarten framework is invaluable for steady-injection thermal estimates but is restricted to constant, unidirectional flow, while full-physics thermo-hydro-mechanical simulators handle arbitrary flow at the cost of hours of computation per run. The thermal reduced-order model (ROM) of Rivas et al. (2026) bridges this gap on the heat-transport side, extending the Lauwerier–Gringarten framework to fully variable flowrates including flow reversals while reducing run times from hours to minutes. In the present work a thermal ROM that draws in part on this formulation is coupled with a nonlinear hydromechanical lumped-parameter ROM (hereafter the hydromechanical ROM) that reproduces the flow and pressure of the huff-n-puff cycle and is calibrated to the field record; the hydromechanical ROM supplies the imposed flow that drives the thermal ROM. Their formulation is developed in Section 3.

This paper concerns the operation of huff-n-puff subsurface systems: lessons from a field-validated mechanical energy storage platform applied to geothermal heat extraction. We calibrate the hydromechanical ROM to the repeatable pressure and flow-rate record of the grid-connected field system, establishing the operating envelope that controls the cycle, and then drive the coupled thermal ROM with this calibrated flow to project how heat extraction via huff-n-puff would operate under representative geothermal conditions. The remainder of the paper is organized as follows. Section 2 presents the field campaign and its per-cycle operating metrics; Section 3 develops the two coupled reduced-order models and their coupling; Section 4 calibrates the hydromechanical ROM to the field data; Section 5 drives the thermal ROM with the calibrated flow to project heat extraction under representative geothermal conditions; and Sections 6 and 7 discuss implications and conclusions.

2. Field Campaign: Geothermal-Representative Huff-n-Puff Cycles at a Grid-Connected Energy Facility

The subsurface system is a single deep well that stores energy mechanically: fluid injected at high rate pressurizes a stimulated fracture system, and that stored pressure is recovered as controlled flowback during production. The concept was first demonstrated at a pilot well in South Texas (Simpkins et al., 2023). The present campaign was conducted at a separate, grid-connected instrumented full-scale surface facility of similar subsurface design. That the cyclic huff-n-puff behavior first observed at the pilot is reproduced here indicates the operation is not specific to a single installation. More broadly, the same single-well cyclic mode underlies the GeneSys district-heating demonstration in Germany (Tischner et al., 2010), confirming it generalizes across geologies and applications.

Over several days, this system operated multiple repeatable injection–production cycles at short time scales. The installation is a grid-connected energy facility with mechanical energy storage capability, but here the cycles were deliberately operated on a schedule meant to emulate a single-well geothermal heat-extraction duty using the huff-n-puff approach (the injection, soak, and production sequence a huff-n-puff geothermal well would follow in general, although the present campaign considers the limiting case without a soak) and are therefore read here as geothermal-representative cycles rather than as a storage demonstration; a soak phase is a natural next step, since it is the interval in which the inter-cycle thermal recovery would develop. These cycles establish that such operations are controllable and repeatable in the field. Although the site's modest geothermal gradient places it below power-production grade, the campaign nonetheless yielded a dense, high-quality record of wellhead pressure and flow rate on which the present model rests.

Beyond the surface facility, the present site shares a subsurface setting broadly similar to the 2023 pilot. The minimum horizontal stress (Shmin) profile across the interval (Figure 1) indicates a comparable stress regime, with three stress barriers bounding the stimulated regions and limiting vertical fracture growth. These barriers define two stimulated intervals, which the model represents as two separate fracture tanks (Section 3). This profile also sets the fracture closure stress used by the model in Section 3. Throughout this paper, stress, pressure, and flow rate are shown in normalized form, to emphasize the qualitative behavior and the cycle-to-cycle repeatability of the operation rather than site-specific absolute magnitudes.

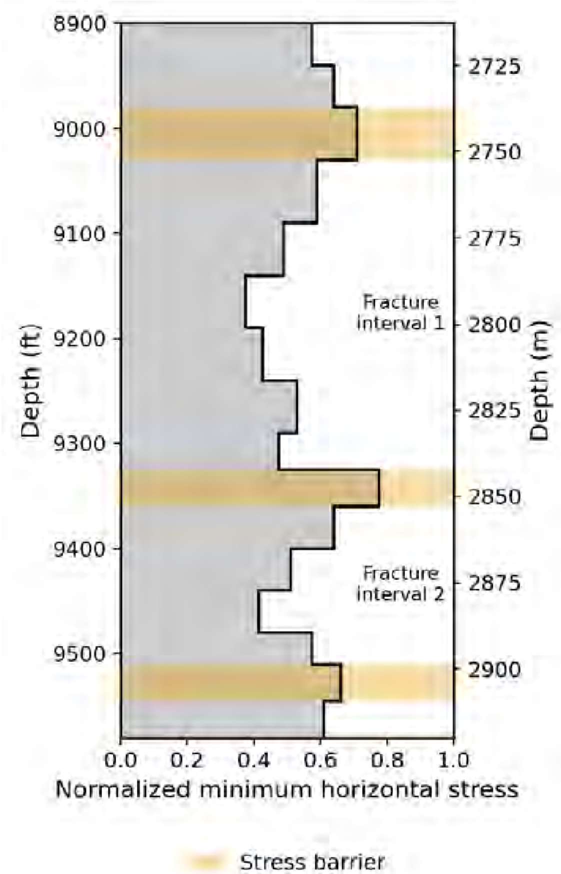

Figure 1: Minimum horizontal stress (Shmin) profile for the present site; the stress axis is normalized.

2.1 Per-Cycle Operating Metrics

The present campaign proceeded in stages. An earlier set of cycles characterized the geosystem and established how it should be operated under huff-n-puff cycling as a heat-extraction duty rather than as energy storage, on a geothermal-representative schedule. A subsequent set of consecutive cycles was then run to demonstrate that the operation is repeatable and controllable, and that it can be sustained through periodic recharge; the campaign afterward continued with further testing. This paper analyzes only that consecutive set, numbered 1 through 18 in what follows. These eighteen cycles are the record to which the hydromechanical ROM is calibrated (Section 4).

Each cycle is summarized by a compact set of operating metrics: the volume balance (injected volume, produced volume, and their ratio as water recovery), the round-trip subsurface efficiency, the injection and production rate schedule, and the sustained injection and production durations.

Three representative consecutive cycles from the campaign illustrate this scheme; their wellhead-pressure and flow-rate records are shown in normalized form in Figure 2 and the corresponding metrics are reported in Table 1.

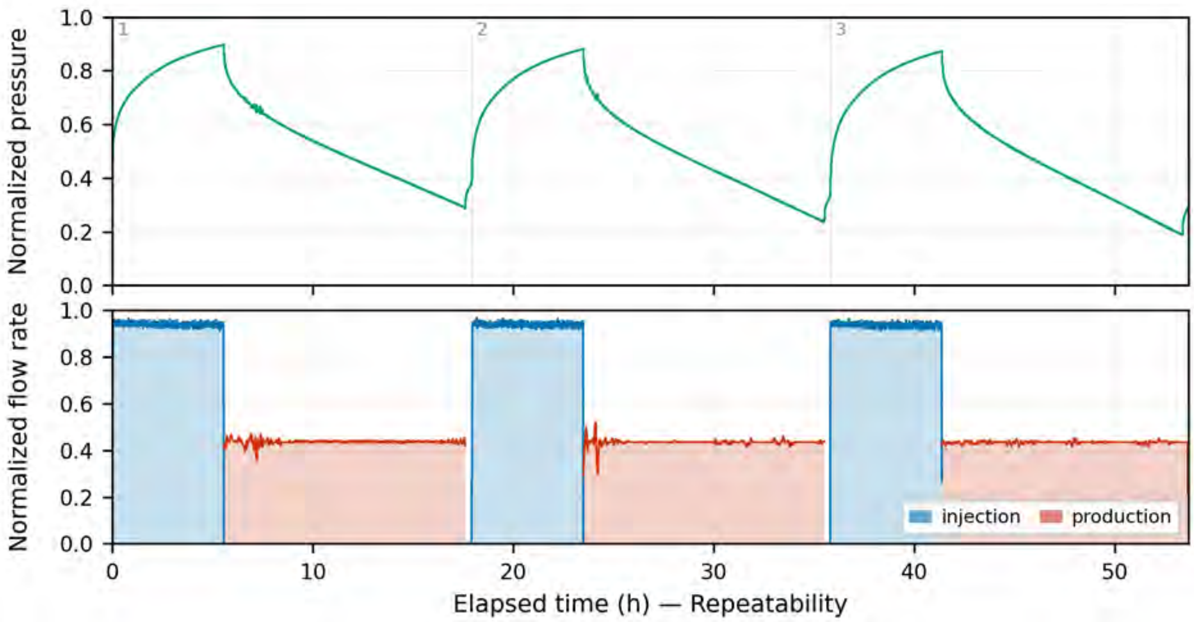

Figure 2: Measured wellhead pressure (top; normalized to ~2500–5000 psi) and flow rate (bottom; normalized by 11.5 bpm; blue = injection, red = production, blank = shut-in) for three consecutive huff-n-puff cycles (1–3) at the grid-connected energy facility, illustrating the per-cycle operating metrics summarized in Table 1.

The injected volume held near 3,600 bbl while the produced volume essentially matched it, giving water-recovery ratios of 99.7–100.0 % (the ratio is capped at 100 % by definition, so in cycles where the produced volume slightly exceeds the injected volume the surplus is drawn from fluid stored in earlier cycles rather than representing a net gain), indicating high measured water recovery over the analyzed cycles; longer repeated operation requires a small make-up injection to offset the modest cumulative migration of fluid into the surrounding matrix. The cycles returned mechanical round-trip (subsurface) efficiencies of 84–86 %, defined as the hydraulic energy recovered divided by the hydraulic energy injected and evaluated at the 100 % water-recovery point. This efficiency remains a meaningful target for a geothermal huff-n-puff system in its own right: it measures how little of the injected hydraulic work is lost over the charge–discharge cycle, so an efficient mechanical side keeps the parasitic pumping cost of operating the well low regardless of whether the recovered energy is taken as pressure or, ultimately, as heat. The rate schedule was equally consistent, with injection sustained near 11 bpm over about 5.6 hours and production held near 5 bpm, yielding roughly 12 hours of sustained production per cycle. The consistency of these metrics across three back-to-back cycles is already evident, with comparable water recovery, sustained multi-hour production, and round-trip efficiency from cycle to cycle; these three cycles are the first of the longer repeatability run examined in the next subsection, which establishes that the operation is repeatable and controllable across the full run.

Each cycle transitions almost directly from production into the following injection, separated only by a short zero-flow turnaround that spans a few percent of the total cycle time, rather than an extended shut-in. This brief pause is a deliberate operating choice, not an incidental gap: it is long enough to reveal the initial post-production pressure rebound as the fracture system begins to re-equilibrate. This rebound is the pressure analog of the inter-cycle thermal recovery on which huff-n-puff heat extraction would ultimately rely (Section 5). The cycles were likewise operated without a post-injection soak, passing directly from injection into production. Earlier modeling of huff-n-puff thermal recovery indicated that an inter-phase soak (shutting in the well between injection and production) can improve inter-cycle thermal recovery (Rivas et al., 2025a); the present campaign deliberately adopts the opposite limiting case of no soak, so that the field record characterizes the soak-free schedule of continuous, back-to-back operation.

Table 1: Per-cycle operating metrics for three consecutive huff-n-puff cycles at the grid-connected energy facility.

Metric	Cycle 1	Cycle 2	Cycle 3
Injected volume (bbl)	~3,600	~3,600	~3,600
Produced volume (bbl)	~3,620	~3,610	~3,590
Water recovery (%)	100.0	100.0	99.7
Subsurface efficiency (%)	86	85	84
Injection rate (bpm)	~11	~11	~11
Production rate (bpm)	~5	~5	~5
Sustained injection (hours)	5.6	5.6	5.6
Sustained production (hours)	12.0	12.0	12.0

2.2 Repeatability Across Eighteen Consecutive Cycles

Extending the analysis from three to eighteen consecutive cycles (Cycles 1–18, Figure 3) shows that the operation is repeatable and controllable across the full run. The rate schedule and cycle timing change little from cycle to cycle: injection holds near 11 bpm and production near 5 bpm, with about 12 hours of sustained production every cycle, and these quantities, together with the overall cycle length, each vary by less than a percent, so the wellhead-pressure and flow records overlay almost exactly. The one clear exception is Cycle 17, where a passing thunderstorm tripped the variable-frequency drive and briefly interrupted injection, producing a double-peaked pressure signature (Figures 3 and 5); because the model is driven by the measured flow, it reproduces even this irregular cycle (Figure 5), reinforcing that the ROM follows the governing physics rather than being tuned to any single record. At this cadence the well completes just over one full huff-n-puff cycle per day, about 1.3 cycles per day (cpd), a convenient measure of how hard the system is operated and one we return to when discussing heat-extraction duty (Section 6).

Sustaining this many back-to-back cycles relies on a periodic recharge. Left uninterrupted, the per-cycle pressure floor drifts gradually downward as fluid leaks off to the formation; a recharge cycle injects additional make-up fluid to lift that floor back up. Recharge cycles are otherwise identical to the regular cycles (production is held at the same rate and duration) and differ only in a longer injection phase, which supplies the extra volume. A single recharge does not fully offset the intervening leak-off, but applied periodically it maintains the operating pressure within a bounded band, so the system can be cycled repeatedly over the run. The campaign continued for additional cycles beyond the window shown; without further recharge over that later stretch the pressure floor drifts lower, consistent with the recharge, rather than any change in the cycle itself, being what holds the operating band.

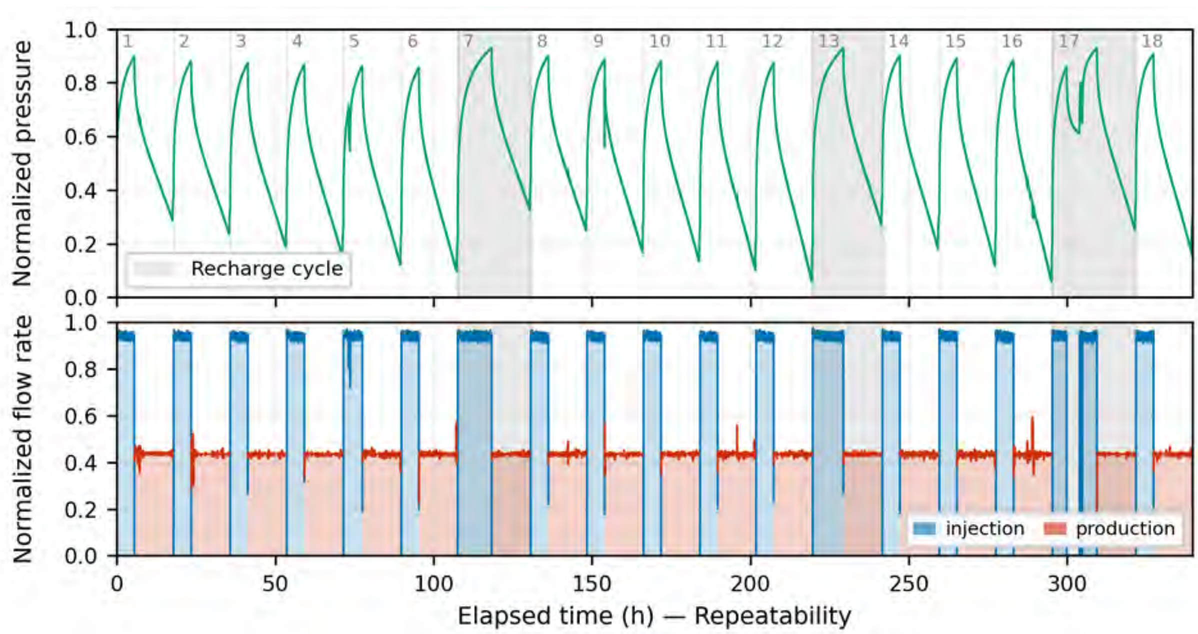

Figure 3: Measured wellhead pressure (top; normalized to ~2500–5000 psi) and flow rate (bottom; normalized by 11.5 bpm; blue = injection, red = production, blank = shut-in) for consecutive huff-n-puff cycles 1–18, demonstrating cycle-to-cycle repeatability of the pressure window and rate schedule. Shaded intervals mark cycles that include a periodic recharge.

3. Reduced-Order Model

The integrated model comprises two coupled reduced-order models: a hydromechanical ROM that resolves the flow and pressure of the huff-n-puff cycle, and a thermal ROM that resolves fracture heat transport. The hydromechanical ROM supplies the flow history that drives the thermal ROM.

3.1 Nonlinear Hydromechanical Lumped-Parameter ROM

The hydromechanical ROM represents the wellbore, the stimulated fracture network, and the surrounding formation as a network of connected tanks, illustrated schematically in Figure 4. The wellbore is treated as a single storage tank driven by the wellhead flowrate; it communicates through a near-wellbore connection with the fractures, each of which in turn leaks off to a halo representing the surrounding formation. The huff-n-puff cycle enters the model only through the sign and magnitude of the wellhead flowrate, so that the same equations describe charging, shut-in, and discharge without modification. This lumped representation places the model within the established tradition of lumped-parameter modeling of geothermal reservoirs, in which a reservoir is idealized as a network of storage elements connected by flow resistances and driven by an imposed mass flow (Axelsson, 1989; Axelsson et al., 2005). That tradition has long been used to simulate and predict pressure response in conventional, largely low-temperature, liquid-dominated systems over years to decades. Here the same network philosophy is adapted to the short, high-rate huff-n-puff cycle and extended from a purely hydrological description to a hydromechanical one, in which fracture storage depends on closure stress and compliance; the regimes differ, but the modeling style is shared.

For a system of N fractures indexed by i, mass conservation on the wellbore and on each fracture gives

$$C_w \frac{dP_{\mathrm{BH}}}{dt} = Q_{\mathrm{WH}} - \sum_i q_{\mathrm{BH}\to i} \tag{1}$$

$$S_i(P_i) \frac{dP_i}{dt} = q_{\mathrm{BH}\to i} - q_{i,\mathrm{leak}}, \quad i = 1 \dots N \tag{2}$$

The fracture pressure is set by a compliance relation of power-law type linking the stored fluid volume to pressure, where the pressure of the i-th fracture, P_i, is a function of the fracture closure (minimum) stress σ_i, a stiffness coefficient K_i, a power-law exponent n_i, and the stored fluid volume.

The near-wellbore and leak-off fluxes are taken proportional to their driving pressure differences,

$$q_{\mathrm{BH}\to i} = \frac{P_{\mathrm{BH}} - P_i}{R_i} \qquad q_{i,\mathrm{leak}} = \frac{P_i - P_p}{R_{\mathrm{halo},i}} \tag{3}$$

Finally, the wellbore (bottomhole) pressure is related to the measured wellhead pressure by a hydrostatic head and a flow-dependent friction loss,

$$P_{\mathrm{BH}} = P_{\mathrm{WH}} + \rho g D - a_{\mathrm{fric}}\, Q_{\mathrm{WH}} |Q_{\mathrm{WH}}| \tag{4}$$

In these expressions, P_{BH} and P_i denote the wellbore (bottomhole) and fracture pressures and C_w the wellbore storage, while Q_{WH} is the wellhead flowrate, positive for injection and negative for production. In Figures 2 and 3, the production rate is plotted as a magnitude in the normalized flow panel. The term $q_{BH\to i}$ is the flow delivered from the wellbore to fracture i across a near-wellbore resistance R_i, and $q_{i,leak}$ is the leak-off, the migration of fluid from fracture i into the surrounding matrix, across a halo resistance $R_{halo,i}$, with P_p the pore pressure. The pressure-dependent storage $S_i(P_i)$ is the slope of the fracture volume–pressure relation implied by the compliance law, in which σ_i is the fracture closure (minimum) stress and K_i a stiffness coefficient. Here P_{WH} is the wellhead pressure, ρ the fluid density, g the gravitational acceleration, D the well depth, and a_{fric} a lumped friction coefficient.

Because σ_i is the closure stress against which fracture i is propped, the minimum-stress profile of Section 2 directly informs this parameter. By construction, the fractures are operated in a pressure-propped, open state: the fracture pressure P_i is held above its closure stress σ_i (the local minimum horizontal stress). Maintaining P_i above σ_i is what keeps the stored volume, and the recoverable pressure work it represents, from being lost to fracture closure between cycles; the stress barriers identified in Section 2 contain vertical growth while the fractures are held in this above-closure condition. For the present site, the two stress-bounded intervals of Section 2 specialize the general formulation to N = 2 fracture tanks (i = 1, 2). The leak-off term $q_{i,leak}$ likewise makes the periodic recharge of Section 2 explicit: it represents the small volume of fluid that migrates from each fracture into the surrounding matrix over each cycle, which the periodic make-up injection replenishes.

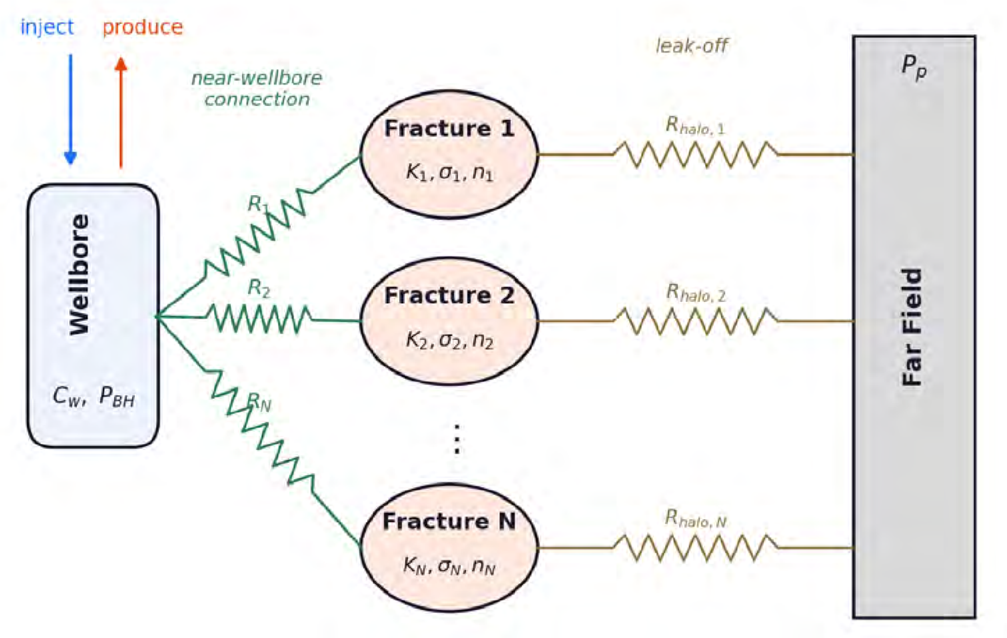

Figure 4: Multi-tank representation of the wellbore–fracture–formation network used by the nonlinear hydromechanical lumped-parameter ROM.

3.2 Thermal ROM and Coupling

The thermal response is represented with a reduced-order thermal model whose per-fracture heat transport draws in part on the model of Rivas et al. (2026), which extends the classical Lauwerier–Gringarten framework to the fully variable, reversing flow of huff-n-puff operation. It reduces the coupled fracture–rock heat-transport problem to a one-dimensional advection equation in the fracture, driven by a temporal memory operator for conduction into the surrounding rock. The two reduced-order models are coupled in one direction: the hydromechanical ROM supplies the flow delivered to the fractures, and this imposed flow drives the thermal ROM. The hydromechanical response is therefore calibrated to the field data independently of the thermal ROM, which serves only to project the wellhead temperature under representative geothermal conditions (Section 5, Figure 6).

4. Calibration to Field Data

The hydromechanical ROM is calibrated to the field measurements of Section 2, anchoring its flow and pressure response to the observed record. Calibration is posed as a nonlinear least-squares problem, the established inverse-modeling approach long used to fit lumped reservoir models to pressure data (Axelsson, 1989; Axelsson et al., 2005), in which the model coefficients are adjusted to minimize the sum of squared residuals between the modeled and measured wellhead pressure history across the repeated cycles. The optimization levers are the coefficients introduced in Section 3.1 (the wellbore storage C_w, the near-wellbore resistances R_i, the halo leak-off resistances $R_{halo,i}$, and the fracture compliance parameters), while the closure stresses σ_i are fixed *a priori* by the minimum-stress profile of Section 2.

Calibrated in this way, a single physics-based parameter set reproduces the measured wellhead-pressure history across all eighteen repeatability cycles closely (Figure 5), with low residuals (a root-mean-square error of about 38 psi, roughly 1% of the operating pressure) through the charge, turnaround, and discharge of each cycle. The same physics and the same fixed coefficients describe every cycle, including the periodic recharge cycles, without refitting from one cycle to the next. This consistency suggests that the model captures the dominant physics of the cycle rather than fitting each record individually. This field-calibrated hydromechanical response provides the field-grounded basis on which the thermal projection of Section 5 is built.

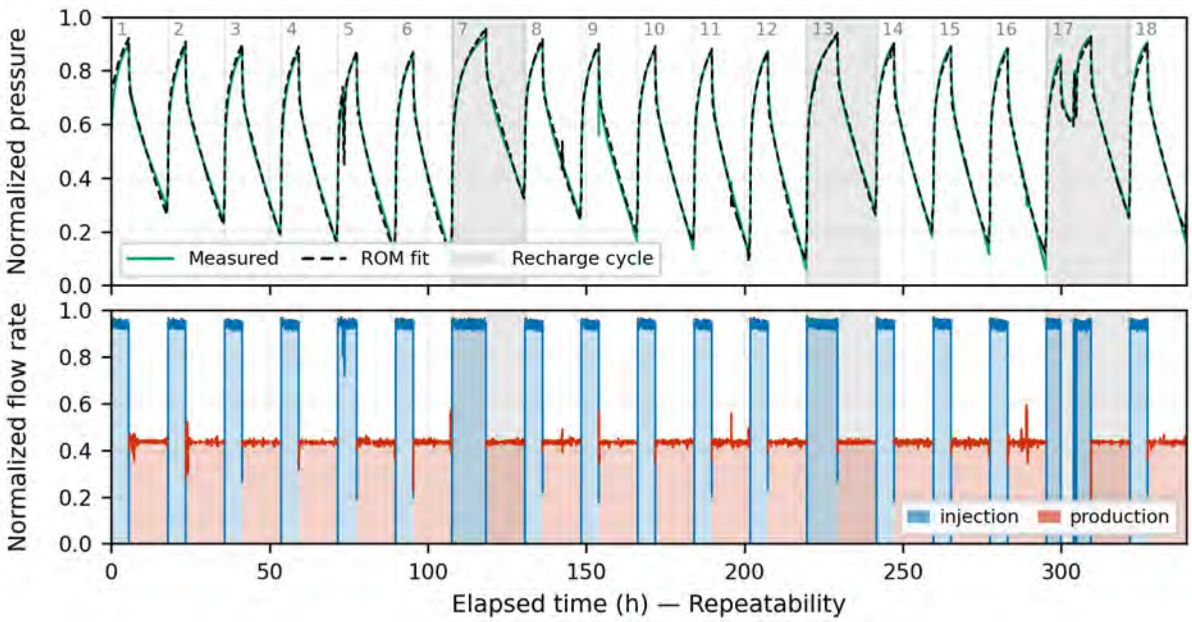

Figure 5: Measured (solid green) and modeled (black dashed) wellhead pressure (top; normalized to ~2500–5000 psi), together with the measured flow rate that drives the model (bottom; normalized by 11.5 bpm; blue = injection, red = production, blank = shut-in) across the eighteen consecutive repeatability cycles. Shaded intervals mark cycles that include a periodic recharge.

5. Thermal Projection

The calibrated cycle now extends from pressure to heat. Under representative power-grade geothermal conditions, a reservoir temperature near 200 °C with 90 °C injectate, the model projects how the produced temperature would build and recover across the repeated cycles, using the calibrated hydromechanical parameters of Section 4. Because the present site is below power-production grade, this is a forward projection rather than a field-validated result, with confirmation at a power-grade resource left to future work.

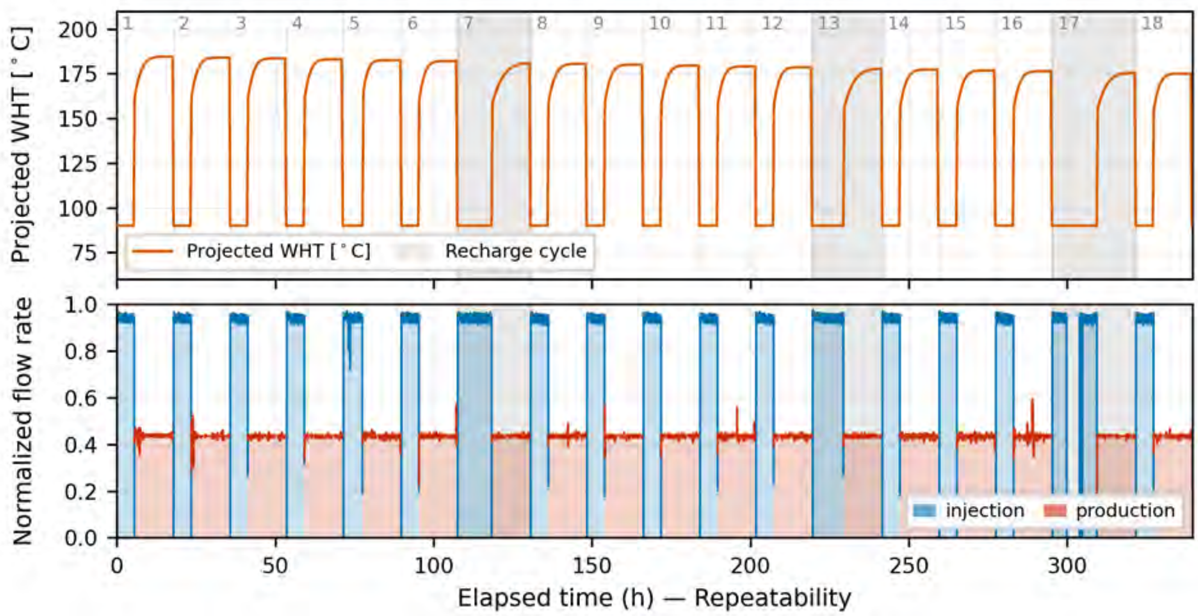

Figure 6: Projected wellhead temperature (WHT) from the coupled thermal ROM (top), driven by the same measured flow rate that drives the calibrated hydromechanical ROM (bottom; normalized flow rate, blue = injection, red = production, blank = shut-in).

Figure 6 illustrates such a projection. Driven by the calibrated flow history, the coupled thermal ROM yields a wellhead temperature that rises through each production phase and returns to the injectate temperature during the intervening injection and turnaround. From one cycle to the next the projected peak temperature declines gradually, reflecting the slow thermal drawdown of the near-well region under repeated cycling. Throughout production, wellhead backpressure is maintained above the saturation pressure of the produced fluid so that the flow remains single-phase liquid, consistent with the assumption underlying both the hydromechanical and thermal reduced-order models.

The projection above corresponds to a single well producing from its stress-bounded subsurface, one unit that would deliver a corresponding amount of power under power-grade conditions. Reaching a higher target output is then a matter of scale: additional fractures, and additional wells, operated on the same cycle. Quantifying that output for a specific resource is left to future work, as the present focus is the operating cycle rather than a power estimate.

6. Discussion

The operating envelope learned from these geothermal-representative cycles (cycle timing, rate scheduling, rebound behavior, and recharge) translates directly into how a heat-extraction huff-n-puff system would be operated.

Because the cycle is controllable and repeatable, a heat-extraction deployment would be operated in the manner demonstrated here: charge by injecting at a scheduled rate and produce on a chosen cadence, with a small periodic recharge that maintains the operating pressure within a bounded band. That same controllability makes the operation grid-responsive (cycles can be timed to electricity price and demand, charging when power is abundant and producing when it is needed) on the hour-to-day scales the field record demonstrates. The same flexibility lets a heat-extraction deployment complement variable renewables: it can charge on surplus wind or solar generation and produce when those sources fall off, helping firm intermittent output toward around-the-clock power.

What the campaign establishes and what the model projects should, however, be kept distinct. The pressure and flow behavior of the cycle (repeatability, round-trip efficiency, volume balance, and rate scheduling) is measured directly by the field data and reproduced by the calibrated hydromechanical ROM (Sections 2 and 4); this is the field-grounded basis of the present work. The thermal behavior is a forward projection (Section 5): because the present site is sub-power-grade, no produced-temperature data exist to confirm it, and the thermal results are best read as physically grounded expectations rather than field-validated outcomes.

The principal new degree of freedom for heat extraction is cadence. How hard and how often the system is cycled is a design lever set by the target project life, and the GeneSys demonstration at Horstberg (Tischner et al., 2010) anchors one end of the spectrum. GeneSys ran gentle, weekly cycles, roughly 3–8 bpm injection and about 3.4 bpm production, and was aimed at a multi-decade district-heating duty, for which modeling projected thermal output declining only gradually from about 1.3 to 0.8 MWth over twenty-five years. The same single-well concept was subsequently applied at a purpose-drilled well in Hannover, aimed at supplying district heat to a research institute (Tischner et al., 2013). The present heat-extraction concept targets a much shorter horizon, on the order of 5 to 10 years, so operating harder, higher rates and the roughly 18-hour cycles seen here, is a deliberate match to that horizon. Both are rational points on a single continuum of the same single-well operation (Table 2); the reduced-order model exists precisely to screen where on that continuum a given project should operate.

Table 2: Approximate operating envelopes of the GeneSys (Horstberg) heat-extraction demonstration and the present campaign, two endpoints of the same single-well huff-n-puff operation. Values are approximate and the comparison is qualitative.

Parameter	GeneSys (Horstberg)	Present campaign
Cycle cadence	Weekly	~18 hours (~1.3 cpd)
Injection rate	~3–8 bpm	~11 bpm
Production rate	~3.4 bpm	~5 bpm
Target project life	Multi-decade	~5–10 yr
Primary application	Heat extraction (district heating)	Energy storage (geothermal-representative cycles)
Setting	N. Germany, ~150 °C	South Texas, sub-power-grade

GeneSys also serves as an independent reality check on the thermal projection: it is the one field case in which huff-n-puff has actually extracted heat at the roughly 1 MWth scale, lending plausibility to the magnitudes projected here even though the setting differs (northern Germany at about 150 °C in the subsurface is not the South Texas target), so the comparison is qualitative. It also demonstrated that the stimulated fracture remained highly conductive across many repeated cycles under large cyclic pressure swings, underscoring the mechanical robustness on which sustained single-well huff-n-puff depends. A physical floor also bounds the cadence lever: cycling faster than the formation can conductively re-heat the near-fracture rock lowers the produced temperature, so the value-maximizing cadence is finite, and identifying it is exactly the task for which the calibrated model is intended.

7. Conclusions

On a geothermal-representative, soak-free schedule, field data from a grid-connected energy facility with mechanical energy storage capability in South Texas demonstrate that a stimulated fracture system can be pressure-charged and then operated in repeatable, controllable single-well huff-n-puff injection-production cycles. Across eighteen consecutive cycles, at about 1.3 cycles per day (cpd), water recovery held at 99.7 to 100.0%, round-trip subsurface efficiency at 84 to 86%, and sustained production at about 12 hours per cycle, with the rate schedule and cycle timing varying by less than a percent from cycle to cycle. Sustaining this many back-to-back cycles is made practical by a periodic recharge, a small make-up injection that maintains the operating pressure within a bounded band over the run and provides a simple, field-tested way to keep the cycle repeatable over extended operation.

The hydromechanical ROM, with the fracture closure stresses fixed a priori from the minimum-horizontal-stress profile of Section 2, reproduces the measured wellhead-pressure history across all eighteen cycles, including the recharge cycles, without refitting from one cycle to the next, matching the record to within about 1% of the operating pressure (a root-mean-square error of about 38 psi) and running in minutes per case. Representing the wellbore, the stress-bounded fracture intervals, and the surrounding formation as a network of connected tanks with a single fixed parameter set, it provides a fast, field-grounded description of the pressure and flow behavior of the cycle and forms the calibrated basis of this study.

Because the present site is below power-production grade, the step from pressure to heat is a projection rather than a measurement. Driven by the calibrated flow, the coupled thermal ROM projects a produced wellhead temperature that builds within each cycle and declines only gradually across the eighteen cycles, under representative power-grade conditions of a reservoir near 200 °C with 90 °C injectate. Validation of this thermal response, and any scale-up toward a target output through additional fractures and wells, awaits a power-grade site.

Taken together, the field record and the calibrated model demonstrate the operating cycle itself, the repeatable, controllable pressure and flow of single-well huff-n-puff, while the heat it would deliver remains a forward projection. They place mechanical energy storage and geothermal heat extraction as two operating points on a single continuum of the same operation, spanning cadences from the weekly cycles of the GeneSys project in northern Germany to the more than one cycle per day shown here. That controllability also makes the operation grid-responsive, able to time its cycles to shifting electricity demand and to firm variable wind or solar toward around-the-clock power. Cadence is therefore a design lever with a finite, physics-bounded optimum to be matched to a given project life and grid duty, since cycling faster than the near-fracture rock can conductively re-heat lowers the produced temperature, and the calibrated ROM makes locating that optimum practical.

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