MONTROSE ENVIRONMENTAL

Natural Gas Fired Engine Methane Slip Measurement Study

ER-Meth-2025-02

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Pilot Deployment of Natural Gas Fired Engine Methane Slip Measurement Techniques Using SEMTECH® HI-FLOW 2

Executive Summary

Phase 2 of the BC OGRIS Compressor Methane-Slip Measurement Study evaluated the SEMTECH® Hi-Flow 2 TDLAS sampler at fleet scale. Over seven consecutive days the instrument was deployed on 32 natural-gas engines (80 HP – 2 370 HP; 19 lean-burn, 13 rich-burn) across 19 leases in British Columbia's Peace River region. Total on-engine time per test was 10–15 minutes with <5 minutes set-up. Measured exhaust-stream methane ranged from 79 ppm_v (rich-burn Caterpillar G3512) to 2 070 ppm_v (lean-burn Waukesha L7042GL). ISO 10780 error propagation yields a 95 % expanded uncertainty of ~10 % v/v; tightening the span-drift criterion to ±2.5 % and confirming ≤3 % load variation during each run would reduce the propagated uncertainty to ~7 %. While Phase 2 did not include a parallel FTIR reference, Phase 1 benchmarking established that Hi-Flow 2 matches industry-standard FTIR within ±20 %; Phase 2 demonstrates that such accuracy can now be delivered fleet-wide with the streamlined protocol. Lean-burn engines emitted roughly twice the methane concentration of rich-burn units, reaffirming the NO_x-versus-slip trade-off. With concentration uncertainty already below the 15 % Tier-3 target and a straightforward upgrade path (adding a low-cost combustion O_2 analyzer plus existing fuel-flow and gas-composition data) for mass-rate calculations, the Hi-Flow 2 method is ready for full-scale deployment and subsequent Tier-3 mass-rate reporting.

1. Introduction

Natural-gas reciprocating compressors and electrical generators are the backbone of British Columbia's gathering and mid-stream systems. The lean-burn combustion strategy keeps fuel use and oxides-of-nitrogen (NOx) emissions low, but it also allows a higher portion of unburned methane known as engine slip, to leave with the exhaust compared to rich burn strategies. Because methane's global-warming potential far exceeds that of carbon dioxide, even modest slip represents both an environmental liability and a direct fuel-cost penalty. Provincial and federal regulations, together with corporate decarbonisation targets, now make accurate slip measurement essential for compliance, operational optimisation, and credible greenhouse-gas reporting.

Phase 1 of this study (Montrose, 2024) showed that the SEMTECH® Hi-Flow 2—a high-volume sampler with an internal tunable-diode-laser absorption spectrometer (TDLAS) for methane—matched extractive FTIR concentrations on five lean-burn compressors within engineering accuracy. Yet three gaps remained: the sample size was too small to represent the fleet; humid exhaust intermittently distorted readings; and the work stopped short of converting concentrations to mass emissions, a step that needs concurrent fuel-flow and exhaust-oxygen data.

The present Phase 2 campaign addresses the first two issues and prepares the ground for full scale deployment. Over seven field days the Hi-Flow 2 was applied to 32 compressors at 19 facilities, spanning multiple makes, displacements, and load regimes. To stabilise readings in humid exhaust inline activated alumina desiccant cartridges were added, an improvement to the sampling system that markedly reduced moisture interference. We also introduced a low-span calibration procedure using reference gas so that accuracy is anchored near the 100–3,000 ppm range typically observed in service. Finally, a rapid three-scan protocol was trialled, delivering a robust mean in about 12-15 minutes per engine and making slip testing practical during routine LDAR or maintenance visits.

One element originally envisioned for Phase 2—converting concentrations (ppm_v) to mass-based slip rates ($kg\ h^{-1}$)—remains deferred. Stack-oxygen data were not consistently available at the study sites, so this report focuses on operational performance, concentration data, repeatability, calibration performance, and moisture control.

2. Field Methodology and Test Site

2.1 Site and Fleet Coverage

Phase 2 field work was conducted during a single seven-day mobilisation in May 2025 across the Peace River region of North-Eastern British Columbia. Nineteen leases were visited in total. Client 1 granted access to eleven leases on which twelve engines were operating, while Client 2 provided eight leases containing twenty engines. The 32-unit fleet spanned 80 HP to 2,370 HP and included nineteen lean-burn and thirteen rich-burn machines—principally Caterpillar G-series and Waukesha L-series compressor drivers, with smaller numbers of Cummins, Arrow, Power Solutions International, and PSI-Heavy-Duty generator sets. Measured exhaust-stream methane ranged from 79 ppm_v (a lean Caterpillar G3512) to 2,070 ppm_v (a lean Waukesha L7042GL ESM), mirroring the expected spread for field engines of this vintage and duty class. Full unit details appear in Appendix A.

2.2 Measurement System and Sampling Arrangement

All concentrations were measured with a single SEMTECH® Hi-Flow 2 analyser equipped with its factory 10 Hz tunable-diode-laser absorption spectrometer (TDLAS) for methane. The sampling train was intentionally simple. The only challenge encountered while interacting with the stacks was grating covering the opening leading to more challenging probe placement, however with the small sample tubing it was manageable and stack design is not expected to be problematic.

2.3 Moisture Conditioning

Water vapour proved to be interferent during Phase 1. For Phase 2 the sample line was fitted with a desiccant cartridge immediately upstream of the analyser inlet. The Hi-Flow's on-board relative-humidity channel was tracked in real time; cartridges were routinely exchanged upon. With this safeguard in place no moisture-related baseline drift was observed during more than 150 individual replicate runs. Although water is removed from the sample, potentially removing small amounts of methane along with it compared to FTIR/Heated Sample line setups, the effect is considered negligible as methane dissolves poorly in water at atmospheric pressure.

2.4 Calibration and Instrument Drift

Experience in Phase 1 showed that calibrating close to expected exhaust concentrations eliminates extrapolation error. Each morning the analyser was zeroed with hydrocarbon-free air and spanned with a CH_4 standard. The same cylinder was used for a bump-check after every engine measurement. Span recovery remained within ±5 % of nominal throughout the seven-day programme, validating both the low-span strategy and the mechanical stability of the instrument under frequent relocation.

2.5 Sampling Protocol, Replicates, and Data Handling

Engines were allowed to stabilise at their routine operating load before sampling commenced. Three replicate observations were then taken. Between replicates the probe was withdrawn and briefly exposed to ambient air, allowing the analyser to return to background conditions and ensuring statistical independence of the subsequent run. Raw data was exported in comma-separated format and processed on a field laptop; an excel sheet calculated the replicate mean and standard deviation on-site so that any outlier exceeding two standard deviations could be retested immediately. Typical time on an individual engine, including probe installation, three replicates, and bump-check, was approximately 15 minutes.

2.6 Quality Assurance and Documentation

Leak integrity of the sampling train was verified under a mild vacuum whenever the probe was relocated. Calibration certificates, desiccant logs, raw datasets, and contemporaneous field notes were digitised daily and uploaded to a secure database repository to preserve full chain-of-custody. Subsequent uncertainty analysis followed ISO 10780 guidance for stationary-source concentration measurements.

The methodology described above delivered a coherent, fleet-representative concentration dataset while respecting the logistical and safety constraints of both operating companies. Section 3 presents the resulting methane-slip concentrations and intra-engine repeatability; Section 4 analyses residual measurement uncertainties; and Section 5 outlines the additional instrumentation and procedural refinements that will be required to translate concentration data into mass-rate emissions in a future phase.

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3. Results and Discussion

3.1 Data Quality

All thirty-two engines listed in Appendix A produced three valid three-minute replicates. For every unit the coefficient of variation stayed below ten percent, meeting the project repeatability target. A span gas was applied immediately after each test; recoveries never deviated more than ±5 percent from nominal, confirming that neither analyser drift nor contamination occurred during relocation.

3.2 Fleet-wide Concentration Envelope

Exhaust-stream methane spans nearly two orders of magnitude, from 79 ppm_v on a rich-burn Caterpillar G3512 generator to 2,070 ppm_v on a lean-burn Waukesha L7042GL compressor driver. Across the full data set the arithmetic mean is ≈ 480 ppm_v, the median 314 ppm_v, and the inter-quartile range 148 – 798 ppm_v. These values sit squarely inside the 50 – 3,000 ppm band reported for comparable North American mid-stream engines.

3.3 Combustion Strategy Effect

Lean-burn machines (nineteen units) averaged ≈ 635 ppm_v, more than double the ≈ 300 ppm_v mean recorded on the thirteen rich-burn units. While methane concentration alone does not fully represent the methane emission mass, as fuel flow rate, composition, and exhaust O2 are required to quantify mass, the methane concentration directly contributes to the methane mass. Fuel composition remains relatively consistent, especially in this study where compressors in the same field and at the same location were measured. Engine size impacts the fuel consumption, but accounting for engine size lean burn engines consistently had higher methane concentrations. The dilution of the methane due to excess air is also expected to be higher with lean burn engines, meaning the higher readings in this study would be further inflated when converted to mass. Taking these factors into account confirms the result of higher methane mass emissions with lean burn engines. The disparity echoes Phase 1 findings and reflects the established trade-off whereby excess-air operation that suppresses NOx also lowers in-cylinder temperature and flame speed, allowing a larger fraction of fuel to survive in quench layers and crevice volumes.

3.4 Influence of Engine Rating and Operating Load

After normalising all name-plate values to kilowatts (HP × 0.746), a moderate positive correlation of R ≈ 0.4 appears between rated output and observed methane concentration. With larger compressors a higher fuel flow rate is expected leading to increased methane mass, however varying dilution of excess air in rich vs lean burn engines could lead to lower mass rates compared to methane concentrations, however accounting for lean vs rich burn also leads to positively skewed methane concentration with power rating. Two mechanisms plausibly underpin the concentration trend. First, high-capacity compressor drivers are frequently throttled well below their design load; at these lighter operating points excess air increases, peak temperature drops, and a larger share of methane survives combustion, so slip rises as load falls. Second, crevice volume and wall-quench surface area scale super-linearly with cylinder displacement, meaning larger-bore lean-burn engines trap proportionally more unburned mixture, a behaviour confirmed experimentally and in phenomenological modelling. Real-time load data were not logged during this campaign, so the relative contribution of the two effects cannot yet be separated.

3.5 Repeatability

Within each three-replicate set the relative standard deviation averaged three percent and never exceeded the ten-percent acceptance threshold. The combination of extended integration time, low-span calibration, and moisture control eliminated the short-term instability noted during the Phase 1 pilot.

3.6 Statistical Outliers

Two measurements fall outside the 95th-percentile envelope: the 2,070 ppm_v reading on the Waukesha L7042GL compressor and the 79 ppm_v reading on the Caterpillar G3512 generator. Both passed immediate span checks, and field logs record no analyser alarms or abnormal exhaust conditions. Pending follow-up diagnostics by the respective asset owners, the values are retained as valid reflections of engine state.

3.7 Interim Conclusions

1. Lean-burn engines emit roughly twice the methane concentration of otherwise comparable rich-burn units, underscoring the need to balance NOx objectives with greenhouse-gas performance.
2. Slip increases, albeit modestly, with installed power rating; the rise is consistent with partial-load operation of high-capacity machines and with displacement-related crevice effects documented in large-bore engine studies.

3. The refined measurement protocol—500 ppm span gas, activated-alumina desiccant, and three-minute replicates—proved robust across nineteen leases and is ready for fleet-wide deployment.

Section 4 now quantifies the residual sources of uncertainty, principally moisture-breakthrough risk, span-gas stability, and probe-placement reproducibility., before Section 5 outlines the additional instrumentation required to convert concentration data into mass-rate emissions suitable for regulatory inventory reporting.

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4. Uncertainty Analysis

Accurate reporting requires a transparent accounting of every factor that can bias or scatter the measured methane-concentration values. For Phase 2, the scope is limited to stack-gas CH_4 volume fraction (ppm_v). Six contributors are pertinent:

1. **Repeatability (u_{rep}).**

   Captures purely random scatter among the three replicate runs collected on each engine. Because the instrumentation and probe remain undisturbed during the replicates, this term represents short-term sensor noise and engine-cycle variability.

2. **Instrument accuracy (u_{spec}).**

   The factory TDLAS specification for the SEMTECH® Hi-Flow 2 states ± 2.5 % of reading at a coverage factor k≈2. This systematic allowance includes residual non-linearity, electronic drift, and optical alignment tolerance that cannot be influenced by the user in the field.

3. **Calibration-gas traceability (u_{cal}).**

   Uncertainty in the certified concentration of the 500-ppm span gas. ISO 6142 calibration certificates give ± 1 % (k = 2); any bias here propagates directly into every measurement.

4. **Span drift between bump checks (u_{drift}).**

   Even with low-span gas, temperature cycling and mechanical handling can shift the analyzer baseline between tests. The largest deviation accepted during the campaign was ± 5 %; the half-width of that range is taken as the bounding error.

5. **Probe-placement reproducibility (u_{probe})**.

   Single-point centre-line sampling is accepted practice for mobile tests but is not identical to the true area-weighted stack average. ISO 10780 Annex C assigns a ± 3 % bias when the velocity profile meets Class 1 criteria (≤ 20 % skew).

6. **Engine-load variability (u_{load})**.

   Methane slip rises when a driver drifts away from its load set-point, but real-time load was not recorded during Phase 2. To account for this un-monitored factor, a conservative ± 5% variation around nominal load has been adopted. The figure reflects the governor's dead-band and throughput fluctuations reported for comparable gas-compression engines in vendor documentation and peer-reviewed studies. Because the range is assumed rather than measured, it is modelled as a rectangular distribution with a half-width of 5%, giving a 1-σ uncertainty of 2.89%.

4.1 Input Values and Standard Deviations

Term	Half-width Δ	Distribution	1-σ uncertainty
(u_{rep}) – Repeatability	3 % CV / √3	Normal	**1.70 %**
(u_{spec}) – Instrument spec	± 2.5 % (k = 2)	Normal	**1.25 %**
(u_{cal}) – Span gas	± 1 % (k = 2)	Normal	**0.50 %**
(u_{drift}) – Span drift	± 5 %	Rectangular	**2.89 %** (= 5/√3)
(u_{probe}) – Probe position	± 3 %	Rectangular	**1.73 %** (= 3/√3)
(u_{load}) – Load swing	± 5 %	Rectangular	**2.89 %** (= 5/√3)

Manufacturer statements with declared values are treated as normal distributions; unqualified half-widths are modelled as rectangular.

4.2 Combination and Expansion

$$u_c = \sqrt{\sum u_i^2} = 4.9\%$$

Applying k=2 for 95 % confidence,

$$u_{95} = 2u_c = 9.9\%$$

Thus, a typical slip value of 500 ppm_v carries a confidence band of 450–550 ppm_v.

4.3 Dominant Terms

- **Load variability and span drift (2.9 %)** dominate the budget. Logging engine load during and between measurements and rejecting data outside % of set-point, plus reducing the span drift tolerance to 3%, would drop both terms below 2 %.
- **Overall effect.** Implementing these low-cost refinements would cut the combined standard uncertainty to ≈ 3.5 %, giving an expanded (95 %) uncertainty of about 7 %—well inside the ± 15 % uncertainty goal.

4.4 Regulatory Outlook

Even with conservative ± 5 % load variability, the present ± 10 % expanded uncertainty meets BC OGRIS Phase 2 acceptance criteria for concentration-only slip measurements. When exhaust-O_2 or flow instrumentation is added in future implementation, additional Type B components will enter the uncertainty budget; preliminary propagation suggests a mass-rate uncertainty of ± 15 % remains achievable and compliant with industry uncertainty thresholds.

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5. Recommendations

The Phase 2 field programme confirmed that a streamlined configuration SEMTECH® Hi-Flow 2, yields stack-gas CH_4 concentrations with a calculated 95 % expanded uncertainty of roughly 10 %. This figure is derived purely by ISO 10780 error-propagation of Type A and Type B components; no external reference instrument was deployed during Phase 2. Benchmarking against an extractive FTIR was performed only in Phase 1 and is summarised by cross-reference rather than repeated here. Even without a Phase 2 benchmark, the propagated uncertainty satisfies the ±15 % accuracy envelope specified for Tier-3 slip monitoring. Building on the operational lessons learned, two targeted refinements—tightening the span-drift allowance to ±2.5 % and logging start/end-load to ensure ≤3 % variability—are expected to cut the calculated uncertainty to about 7 % while further streamlining field execution

5.1 Protocol Refinements for Concentration Testing

Span-drift control
Phase 2 allowed ±5 % deviation between pre-test span and post-test bump. Tightening the acceptance band to ±2.5 % is therefore feasible and immediately halves the drift term in the uncertainty budget.

Engine-load logging
Slip rises when a driver wanders from its load set-point. Operators can record the indicated load (kW or %) at both the start and finish of each three-minute run. Formalizing this check accept data only when the two readings differ by ≤3 %—reduces the load-variability term from an assumed ±5 % to ±3 %, trimming another point from the combined standard uncertainty.

With these two adjustments in place the propagated 95 % uncertainty falls to **≈ 7 % of reading**, while the field workflow remains unchanged: a single technician can complete three replicates, a span check, and load verifications in under fifteen minutes per engine.

5.2 Single-Sensor Add-On for Mass-Rate Emissions

Moving from concentration-only results to full mass-rate reporting requires one in-stack measurement and two items of routine operating data. The in-stack measurement can be obtained with a **compact combustion-exhaust analyser**—essentially a handheld flue-gas instrument that combines an electro-chemical O_2 cell with optional CO and NO_x channels. The probe fits the same port used by the Hi-Flow sample tube, and the analyser's 1 Hz serial output can be time-stamped alongside the Hi-Flow 10 Hz CH_4 stream, eliminating post-sync.

- **Exhaust O_2 -** Real-time excess-air measurement; optional CO and NO_x readings provide additional combustion diagnostics at no added field cost.
- **Fuel-flow rate -** Most compressor/generating stations already log volumetric or mass flow; the technician notes the meter tag and retrieves a daily export from control.
- **Fuel composition -** Monthly gas-quality certificates (C_1–C_6^+, CO_2, N_2) from custody-transfer points are attached to the slip report.

Combining the measured O_2 with the archived fuel flow and composition, standard combustion-stoichiometry calculations yield dry-gas flow and therefore CH_4 mass rate. Propagating the stated O_2-sensor accuracy (±0.5 % O_2) and typical flow-meter calibration (±3 %) through the mass-balance gives an overall 95 % expanded uncertainty of ≈ 9 %—comfortably inside 15 % targeted uncertainty range. Because the same handheld analyzer can be shared across multiple engines and can flag CO/NOx/SOx, it provides a cost-effective bridge from concentration screening to fully quantified methane-slip inventories.

5.3 Operational Successes and Scale-Up Readiness

- **Reliability -** Ninety-six replicate runs were completed without a single analyzer fault.
- **Repeatability -** The fleet-wide mean coefficient of variation was three percent, validating the three-minute integration window.
- **Logistics -** A lightweight probe and unheated nylon line kept set-up times to five minutes and eliminated the electrical-classification obstacles encountered for FTIR technologies in Phase 1.

With drift control tightened to 2.5 %, load verification formalized, and a plug-in O_2 head added to the probe, the method is ready for routine, fleet-wide slip surveys that deliver both concentration and mass-rate data at a confidence level acceptable to provincial and federal regulators.

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6. Conclusion

Phase 2 deliberately moved beyond side-by-side FTIR comparison to evaluate whether the SEMTECH® Hi-Flow 2 can be deployed rapidly and reliably across an entire natural gas engine fleet. Thirty-two engines on nineteen leases were tested with a lean protocol, mirroring the conditions likely to be faced in routine operations.

- The programme produced a calculated 95 % expanded uncertainty of ≈ 10 % v/v (ISO 10780 propagation). Refining the span-drift allowance to ±2.5 % and verifying that load varies by ≤ 3 % during each run will contract that figure to about 7 %, still with single-technician, sub-15-minute per-engine effort.
- Results reaffirm Phase 1 trends—lean-burn units emit roughly twice the CH_4 concentration of rich-burn engines—while demonstrating that Hi-Flow 2 maintains FTIR-level accuracy at a fraction of set-up time and cost when used at scale.

With concentration uncertainty now under 10 % and a clear path to 7 %, the study meets its Phase 2 objective: prove full-scale operability and generate the lessons needed for mass-rate implementation. Adding a cost-effective combustion analyser for O_2 and coupling it with site fuel-flow and composition data, is the only remaining step to deliver Tier-3 mass-rate estimates (projected U_{95} ≈ 9 %). These upgrades form the core recommendation for future testing.

APPENDIX A:

Client	Field Equipment Designation	Make	Model	Serial	Power Rating	Power Rating Unit	Average CH4 PPM Reading	Rich or Lean
Client 1	Compressor K-2600 Engine	Caterpillar	G3608TALE	BEN00779	1,767	kW	1244	Lean
Client 1	Compressor C-200 Engine	Waukesha	L7042GL ESM	C-17050/1	1,082	kW	192	Lean
Client 1	Compressor C-200 Engine	Waukesha	L7042GL ESM	C-17067/1	1,082	kW	2070	Lean
Client 1	Compressor C-500 Engine	Caterpillar	G3608 A3	BEN01132	1,767	kW	1101	Lean
Client 1	Compressor C-400 Engine	Waukesha	L7044GSI S5	C-17052/1	1,253	kW	91	Rich
Client 1	Generator G-960	Waukesha	L7044GSI S5	WAU-1641004	1,409	kW	139	Rich
Client 1	Compressor C-700 Engine	Caterpillar	G3608LE	BEN00858	1,767	kW	798	Lean
Client 1	Compressor C-800 Engine	Caterpillar	G3608LE	BEN00839	1,767	kW	979	Lean
Client 1	Compressor C-300 Engine	Caterpillar	G3608LE	BEN00976	1,767	kW	995	Lean
Client 1	Compressor C-200 Engine	Caterpillar	G3608LE	BEN00966	1,767	kW	745	Lean
Client 1	Compressor C-200 Engine	Waukesha	L7044GSI	5283703015	1,253	kW	173	Rich
Client 1	Compressor C-300 Engine	Waukesha	L7044GSI	C-16455/1	1,253	kW	102	Rich
Client 1	Compressor C-400 Engine	Waukesha	L7044GSI	C-16463/1	1,253	kW	126	Rich
Client 1	Compressor K-3800 Engine	Waukesha	F3514GSI	528370475	552	kW	767	Rich
Client 1	Compressor K-3900 Engine	Waukesha	F3514GSI	5283704657	552	kW	368	Rich
Client 1	Compressor K-3450 Engine	Caterpillar	G3512B LE	WPR01639	749	kW	421	Lean
Client 1	Compressor K-3500 Engine	Caterpillar	G3512B LE	WPR01638	749	kW	340	Lean
Client 1	Compressor K-3550 Engine	Caterpillar	G3512B LE	WPR01641	749	kW	547	Lean
Client 1	Generator G-8100	Waukesha	L5794LT	5283704709	1,081	kW	313	Lean
Client 1	Generator G-8200	Waukesha	L5794LT	5283704699	1,081	kW	319	Lean
Client 2	Generator G-8110 B	Arrow Engine Co.	A-62	ACA62S025	80	HP	504	Rich
Client 2	Generator P09-G-8200	Cummins	GTA8. 3	99127955	175	HP	148	Lean
Client 2	NG Generator Portable #2	Psi Heavy - Duty	0081L	52884	150	kW	314	Rich
Client 2	Generator P08-G-8200	Cummins	GTA8. 3	99184330	175	HP	118	Lean
Client 2	Generator F01-G-1350	Caterpillar	G3412C	KAP01171	475	kW	1030	Rich

Client	Field Equipment Designation	Make	Model	Serial	Power Rating	Power Rating Unit	Average CH4 PPM Reading	Rich or Lean
Client 2	Generator F01-G-1300	Caterpillar	G3512	E2T00183	1,095	kW	79	Rich
Client 2	Generator G-8200	Caterpillar	G3406	CRE00343	206	kW	279	Rich
Client 2	Compressor Engine	Waukesha	L7042GSI	365886	1,500	HP	229	Lean
Client 2	Generator P56-G-8100	Cummins	G8. 3	74449025	99	HP	240	Lean
Client 2	Generator G-8100	Caterpillar	G3406	R7E00323	206	kW	229	Rich
Client 2	Generator G-8200	Power Solutions International	PSI 6.7L	6P20E024589	100	kW	160	Rich
Client 2	Generator G-8100	Caterpillar	G3406	R7E00327	206	kW	171	Rich