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High-Altitude Hypoxia Analysis and Performance Optimization of a Portable Oxygen Concentrator

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Abstract: *Extreme high-altitude hypoxia challenges both human physiology and the function of portable oxygen concentrators (POCs). This study evaluates a pulse-based POC at elevations from 4400 m to 7546 m, using real-world data collected during a Mount Muztagh Ata expedition and validated through hypobaric chamber simulations. Results reveal significant performance degradation above 6200 m, with concurrent declines in oxygen concentration and pulse flow, indicating the device's operational limits. To address these issues, three lightweight optimization strategies were developed—compressor rhythm adjustment, battery management refinement, and trigger logic enhancement. Chamber tests at 6000 m and 8000 m demonstrated marked improvements in oxygen output, confirming the effectiveness of these strategies without hardware modification.Additionally, the study assessed the applicability of the U.S. Standard Atmosphere model in high-altitude conditions. While the model generally reflects pressure–oxygen trends, discrepancies at extreme elevations highlight the need for temperature corrections in altitude modeling.These findings offer both field-validated data and engineering solutions to support the design and deployment of portable oxygen systems in high-altitude medical, expeditionary, and emergency scenarios.*

Keywords: *High-Altitude Hypoxia, Portable Oxygen Concentrator, Field Testing, Performance Optimization, Hypobaric Chamber Experiment*

1. Introduction

Hypobaric hypoxia at extreme altitudes imposes physiological stress, including reduced oxygen saturation and increased respiratory burden[1]. Portable oxygen concentrators (POCs) are widely used for supplemental oxygen in medical and expedition settings. However, their performance also declines under low-pressure and low-temperature conditions, limiting oxygen delivery when it is most needed.

Most studies on POC performance rely on simulations or theoretical models[2-4], which cannot fully capture the dynamic conditions of high-altitude use—such as rapid pressure shifts, prolonged operation, and extreme cold. As a result, real-world data above 6000 m remain scarce.

This study presents field measurements of a pulse-mode POC on Mount Muztagh Ata (7546 m), validated via hypobaric chamber tests across altitudes. Based on identified limitations, three lightweight optimization strategies are proposed and experimentally verified. The study also examines the applicability of standard atmospheric models for altitude-related oxygen modeling and offers guidance for future system design.

2. Methods

2.1. Field Measurements and Data Collection

Five representative altitude points along the climbing route of Mount Muztagh Ata were selected for testing, covering the range from the oxygen adaptation zone to the extreme high-altitude zone. At each location, the following parameters were measured:

- **Ambient pressure and temperature**, using a mountaineering wristwatch;
- **Oxygen concentration and instantaneous flow rate** at the device outlet, using a handheld airflow analyzer (Model: Fluke V900A).

Three measurements were taken at each location, and average values were used in subsequent

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analysis. These data were used to evaluate the device's oxygen output capacity, flow characteristics, and energy efficiency under real-world environmental conditions.

Table 1: Environmental Characteristics at Each Test Location

Test Point	Altitude (m)	Environmental Features
Base Camp	4400	Low pressure, high oxygen demand; adaptation phase with minimal supplemental oxygen use.
Camp 1	5500	Mixed scree and snow terrain; significant pressure drop.
Camp 2	6200	Glacier crevasse area; pronounced hypoxic conditions.
Camp 3	6900	Final camp before summit; near-maximum altitude.
Summit	7546	Extreme elevation; lowest ambient pressure and oxygen content.

Environmental features recorded at five representative altitudes during the Mount Muztagh Ata expedition, including terrain type and degree of hypoxia. As shown in Table 1, these conditions provide context for interpreting device performance under varying high-altitude environments.

2.2. Hypobaric Chamber Test Setup

To evaluate the device's performance under standardized extreme conditions, a hypobaric chamber was used to simulate high-altitude environments. The chamber's pressure was adjustable within a range of 101.3–35 kPa, covering altitudes from 0 to 8800 meters. The internal temperature was maintained at 20 ± 2 °C. During the test, the device was operated at its maximum setting (S level), and oxygen concentration and equivalent flow rate were recorded at each simulated altitude as a supplement and cross-validation to the field test results.

2.3. Flow Rate Definition and Equivalent Calculation

The tested portable oxygen concentrator operates in a pulsed delivery mode with seven selectable flow settings. Each setting corresponds to a fixed oxygen output rate (ml/min). The device automatically detects the user's inhalation and delivers a corresponding pulse. The actual pulse volume varies depending on the user's breathing rate, as the flow rate is evenly distributed across breaths.

To standardize comparison across tests, an assumed respiratory rate of 20 breaths per minute (bpm) was used to calculate the estimated pulse volume under each flow setting. The equivalent parameters are summarized as follows:

Table 2: Equivalent Oxygen Flow Rate and Calculated Pulse Volume (Assuming 20 bpm)

Setting	Equivalent Flow Rate (ml/min)	Calculated Pulse Volume (ml @ 20 bpm)
1	210	10.5
2	420	21.0
3	630	31.5
4	840	42.0
5	1050	52.5
6	1260	63.0
7	1470	73.5

Equivalent flow rates for each device setting are based on fixed oxygen output per minute. Pulse volumes were calculated by dividing the output rate by an assumed breathing frequency of 20 breaths per minute; actual pulse volumes may vary with the user's real-time respiratory rate. From Table 2, it can be seen that the maximum output (Setting 7) provides an estimated pulse volume of 73.5 ml, which was used in all subsequent performance tests to ensure comparability.

3. Results and Analysis

3.1. Validation of Pressure and Oxygen Partial Pressure Model

To quantitatively assess the variation of oxygen partial pressure with altitude in hypoxic highland environments, field data were collected at five representative elevations along the Muztagh Ata ascent. Ambient pressure and temperature were measured on-site to validate the applicability of the U.S. Standard Atmosphere model and to estimate oxygen partial pressure trends. Deviations between

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modeled and measured values were analyzed to define the model's valid range.

Field data explanation:

- Ambient pressure was recorded using a wrist-mounted barometer, reflecting the actual breathing environment.
- Ambient temperature was recorded simultaneously to evaluate its influence on model deviation.
- Oxygen volume fraction was assumed constant at 20.9%, and partial pressure was calculated accordingly.
- Modeled oxygen partial pressure was computed by multiplying the modeled atmospheric pressure by the oxygen volume fraction.

The standard atmospheric pressure model used for comparison is given by the following equation[2]:

$$P=P_0*(1-\frac{L*h}{T_0})^{\frac{gM}{RL}} \quad , \; P_{O_2}(h)=P(h)*0.209$$

Where:

P(h): Pressure at altitude h (Pa)

P_0: Sea-level standard atmospheric pressure (101325 Pa)

L: Temperature lapse rate (0.0065 K/m)

T_0: Sea-level standard temperature (288.15 K)

g: Gravitational acceleration (9.80665 m/s²)

M: Molar mass of air (0.0289644 kg/mol)

R: Universal gas constant (8.31432 J/(mol·K))

Table 3: Comparison of Measured and Modeled Pressure and Oxygen Partial Pressure

Altitude (m)	Measured Temp(°C)	Measured Pressure(kPa)	Modeled Pressure(kPa)	Measured P_{02}(kPa)	Modeled P_{02}(kPa)
4400	3	60.1	58.49	12.59	12.25
5500	-3	52.2	50.51	10.94	10.58
6200	-10	48.1	45.9	10.08	9.62
6900	-17	44.1	41.64	9.24	8.72
7546	-22	41.1	38	8.61	7.96

Field measurements of atmospheric pressure and oxygen partial pressure are compared with predictions from the U.S. Standard Atmosphere model. As seen in Table 3, measured pressures are consistently higher than the modeled predictions, mainly due to warmer-than-assumed field temperatures. Deviations are mainly due to measured field temperatures being higher than those assumed in the model.

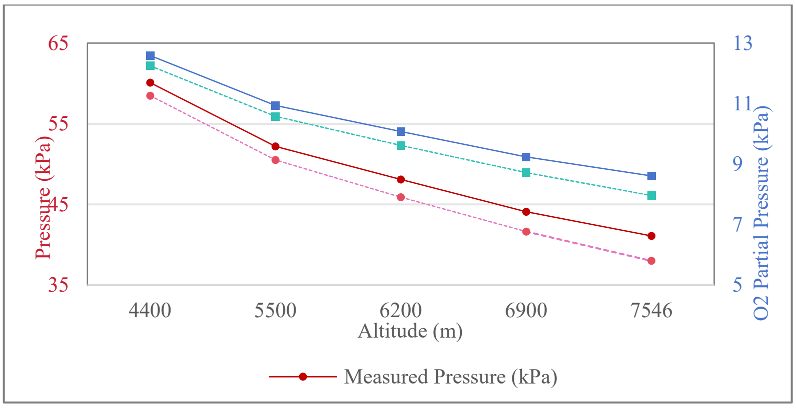

Figure 1: Comparison between Measured and Modeled Atmospheric Pressure and Oxygen Partial Pressure at Different Altitudes

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As shown in Figure 1, measured pressures are consistently higher than the modeled predictions, primarily due to field temperatures exceeding those assumed in the model (e.g., -22 °C measured at 7546 m vs. -34 °C modeled). Deviations in oxygen partial pressure remain within +0.65 kPa, supporting the model's general validity along the route. These results provide a solid foundation for performance modeling in subsequent sections.

3.2. Performance of the Oxygen Concentrator at Different Altitudes

To assess the device's operational stability and output trends under hypobaric conditions, oxygen concentration and equivalent pulse flow rate, were measured at all five field locations using the highest setting (S-level). Each parameter was averaged over three trials.

Table 4: Field Performance Data (@ S Level)

Altitude (m)	O_2 Concentration (%)	Pulse Flow (L/min)	Power (W)	Energy per Liter(W/L)
4400	93	1.58	61	38.61
5500	88	1.52	44	28.95
6200	85	1.48	41	27.7
6900	81	1.33	37.5	28.2
7546	76	1.28	35	27.34

Field measurements of oxygen concentration, pulse flow, power consumption, and energy efficiency at five altitudes, with the device operating at its maximum output setting (S-level). Energy per liter is calculated as Power ÷ Flow rate to evaluate oxygen production efficiency. From Table 4, it is evident that both oxygen concentration and pulse flow decrease steadily with altitude, with a marked decline above 6200 m. Power values are estimated from battery discharge data and internal device logs.

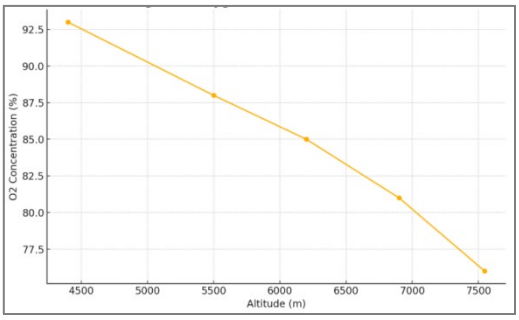

Figure 2: Oxygen Concentration vs Altitude

As illustrated in Figure 2, the oxygen concentration declines linearly with altitude, dropping to 76% at 7546 m, indicating reduced separation efficiency due to lower environmental pressure.

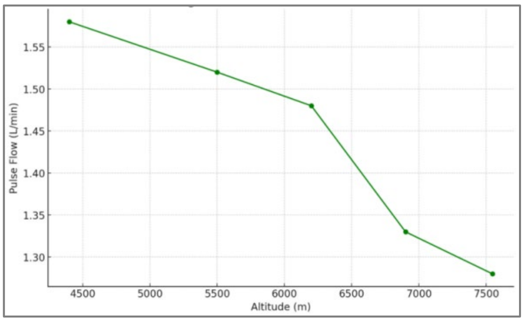

Figure 3: Pulse Flow vs Altitude

As shown in Figure 3, pulse flow also declines, particularly after 6200 m, revealing limitations in both volume and purity under extreme conditions.

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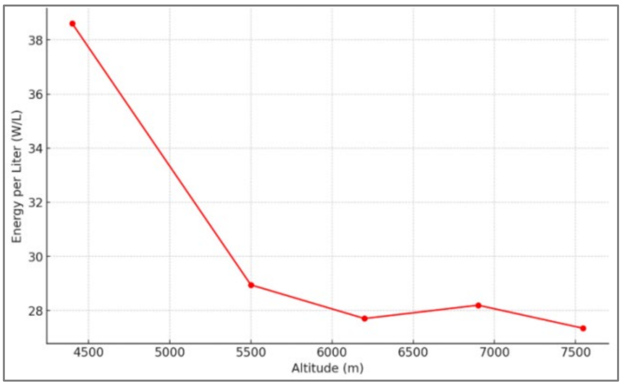

Figure 4: Energy per Liter vs Altitude

As presented in Figure 4, energy efficiency remains mostly stable (27–29 W/L), it spikes significantly at 4400 m (38.61 W/L), indicating potential mismatches in control strategy or energy overshoot.

The overall trend indicates that both oxygen concentration and pulse flow rate decrease steadily with increasing altitude, reflecting the intrinsic performance limitations of oxygen concentrators in low-pressure high-altitude environments. Specifically, the oxygen concentration dropped from 93% at 4400 m to 76% at 7546 m, while the pulse flow rate declined from 1.58 L/min to 1.28 L/min—both showing approximately 18–19% linear reductions. Our findings align with previous simulation studies. For instance, Bunel et al. evaluated four portable oxygen concentrators under simulated conditions at 2438 m, 4200 m, and 8000 m, and found consistent declines in oxygen concentration and flow output, particularly at maximum flow settings[3]. These results confirm the universal challenge high-altitude environments pose to portable oxygen delivery.

This phenomenon can be clearly explained from a gas physics perspective. As altitude increases, ambient pressure and oxygen partial pressure both decrease, leading to a reduced number of oxygen molecules per unit volume. Although the pulse volume per breath remains constant, the total number of oxygen molecules delivered per pulse declines, resulting in reduced "effective oxygen delivery." Thus, the device faces dual limitations: decreasing separation efficiency and a continuously lowered oxygen baseline. Notably, this dual decline leads to a multiplicative—not merely additive—impact: the drop in oxygen concentration reduces the "quality" of oxygen, while the decline in flow volume compresses the "delivery quantity," jointly causing a much greater reduction in actual oxygen uptake than either parameter alone would suggest.

Regarding power consumption, results show a downward trend at higher altitudes (from 61 W to 35 W), likely due to several factors: reduced compressor load with lower pressure, battery voltage drops under cold conditions, and decreased pneumatic resistance in rarefied air. However, energy efficiency (W/L) did not improve correspondingly. At 4400 m, an anomalously high value of 38.61 W/L was observed, far above the 27–29 W/L range seen at higher altitudes, suggesting non-linear energy control inefficiencies—possibly due to suboptimal control algorithms, redundant output, or high trigger sensitivity causing ineffective pulses.

Overall, the device showed accelerated performance degradation above 6200 m, indicating proximity to system limits under ultra-high-altitude operation. Between 6900 m and 7546 m, the decline continued without reaching a steady-state or protective plateau, suggesting the system had not yet entered an auto-threshold protection mode or physical bottleneck zone, but remained in a continuous performance decay phase.

3.3. Optimization Strategies and Chamber Verification

3.3.1. Optimization Strategies

To address the observed decline in oxygen concentration and the elevated energy consumption per liter above 6200 meters, we explored a non-invasive optimization approach based on the working principles of dual-tower pulsed pressure swing adsorption systems. Similar rhythm-based control concepts have been applied in continuous oxygen systems. For example, Rama Rao et al. demonstrated that adjusting adsorption and desorption cycles could significantly improve oxygen yield per unit energy in dual-bed systems[4]. Although their study focused on continuous mode, their approach to

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parameter tuning provides valuable insights for control strategy design. Inspired by this, we proposed three lightweight optimization strategies that could be implemented without hardware modifications: compressor rhythm adjustment, battery management optimization, and improved trigger detection logic. These strategies aim to enhance oxygen output and efficiency under high-altitude conditions. The proposed methods are detailed below:

- **Compressor rhythm tuning:** By adjusting the compressor ratio and working frequency, the intake process can dynamically adapt to varying ambient pressures at different altitudes. Further optimization may include fine-tuning motor cycles and frequency modulation to achieve better energy balance under light-load compression.
- **Battery management optimization:** Power delivery was optimized by introducing voltage buffering and pulse modulation strategies, particularly during high-altitude high-load operation. By slowing the discharge pace and reducing voltage platform collapse, system robustness is enhanced. This approach aligns with the voltage drop alarm requirements outlined in IEC 60601-1-8.
- **Improved trigger detection logic:** The trigger algorithm was refined to improve inhalation detection accuracy, reducing false triggers and delayed responses.

These strategies are all feasible for engineering implementation and can be integrated into existing systems via firmware updates and control logic adjustments. Leveraging onboard environmental pressure sensing, the device can dynamically adjust operating parameters across varying altitudes to achieve a balance between oxygen performance and energy efficiency.Based on these strategies, a series of verification tests were conducted using the hypobaric chamber.

3.3.2. Chamber Verification

Parallel tests were conducted on the pre-optimization and post-optimization device configurations under simulated conditions at 6000 m and 8000 m[4], representing critical performance points. At each altitude, oxygen concentration and equivalent flow rate were measured, and energy per liter (W/L) was calculated as a composite performance metric. Results are shown in Table 5.

Table 5: Performance Comparison Before and After Optimization

Altitude (m)	O_2 Concentration (%) Before	O_2 Concentration (%) After	Flow Rate (L/min) Before	Flow Rate (L/min) After
6000	86.3	91.5	1.48	1.45
8000	70.9	85	1.21	1.35

Hypobaric chamber test results at simulated altitudes of 6000m and 8000m, comparing oxygen concentration and flow rate before and after applying the optimization strategies. At 6000m, oxygen concentration increased by ~5 percentage points with flow rate remaining stable, while at 8000m, concentration improved by over 14 percentage points along with a notable flow rate increase.

3.3.3. Limitations and Notes

It is important to note that the before-and-after optimization data in Table 5 were both collected under tightly controlled, repeatable chamber conditions. This ensures direct comparability within the same environment. In contrast, field data collected at 6200 m and 7546 m are subject to substantial environmental fluctuations, battery state variations, and temperature instability, making them unsuitable as baseline references for optimization evaluation.

Although the chamber results show good consistency and reliability, further long-term field trials are required to fully verify the device's operational stability and effectiveness in real-world high-altitude conditions.

4. Discussion

4.1. Reliability and Applicability of the Model

To better understand the variation of oxygen partial pressure in high-altitude environments, the International Standard Atmosphere (ISA) model was adopted in this study. The model employs typical constants such as the temperature lapse rate L=0.0065 K/mL, sea-level standard atmospheric pressure P_0=101325 Pa, and standard temperatureT_0=288.15 K, to calculate theoretical atmospheric pressure and oxygen partial pressure at different altitudes. Due to its wide application in aeronautical and

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environmental engineering, the model is generally considered robust and reliable.

To verify the model's applicability within the studied altitude range (4400–7546 m), we compared measured field data at five representative elevation points—including atmospheric pressure and oxygen partial pressure—with values predicted by the model. The resulting deviations are summarized as follows:

- Pressure deviation: +3.1 kPa
- Oxygen partial pressure deviation: +0.65 kPa
- Coefficient of determination: $R^2 \approx 0.991$

These results demonstrate that the model has high precision and applicability for the 4400–7546 m range studied. It is particularly suitable for evaluating the external environmental input conditions of oxygen devices under high-altitude hypoxic scenarios.

It should be noted, however, that the primary source of deviation is not computational error, but rather the assumption of temperature in the model, which often differs from actual field conditions. For example, at the 7546 m site, the measured temperature was −22 °C, while the model assumes −34 °C, resulting in a 12 °C deviation. Given the model's exponential sensitivity to temperature, even small temperature deviations can lead to notable pressure discrepancies.Therefore, in future applications requiring more precise simulations or dynamic high-altitude control tasks (e.g., closed-loop regulation or extreme environment forecasting), it is recommended to incorporate real-time measured temperature data to calibrate the model, thereby improving its local adaptability and on-site reliability.

Furthermore, given the validated accuracy of the model across multiple measurement sites, we used it to define environmental boundary points in chamber experiments at 6000 m and 8000 m. The oxygen partial pressure and atmospheric pressure used in these tests were derived from this model, serving as both background references and simulation input values.

In summary, the ISA model demonstrated sufficient reliability within the scope of this study and can serve as a stable foundation for performance prediction and external condition evaluation of oxygen concentrators operating under extreme environments.

4.2. Adaptability and Real-World Constraints of the Optimization Strategies

The three proposed optimization strategies—compressor rhythm tuning, battery management, and trigger logic refinement—are software-level upgrades that require no hardware changes. Their engineering feasibility is high, making them suitable for rapid deployment on existing devices. Chamber tests at 6000 m and 8000 m showed significant improvements in oxygen concentration and flow performance, especially under low-pressure extremes. These results suggest strong adaptability across altitude levels, making the strategies promising for scenarios such as high-altitude emergencies, short-term missions, and field medical use.

However, the strategies assume the original device has some performance margin under normal pressure. If the hardware is already near its output limit, the optimization space at high altitude will be constrained. Additionally, certain adjustments—such as compressor timing—may require fine-tuning for different device models. Chamber testing also has limitations: it can simulate low pressure but not low temperature at the same time. In real environments, fluctuating temperatures, wind, and variable breathing patterns can affect battery behavior, trigger accuracy, and system sealing—factors that can only be validated through field testing.

Despite these constraints, the demonstrated improvements suggest strong potential. Future designs should retain algorithmic flexibility to allow adaptive control tuning under varying environmental loads. This foundation will support more intelligent and robust oxygen systems in future high-altitude or extreme-use applications.

4.3. Future Research Directions

This study, through both field testing and hypobaric chamber validation, has established a preliminary performance evaluation framework for portable oxygen concentrators operating in high-altitude extreme environments. It also proposed generally applicable optimization strategies. However, to address more complex conditions—including long-term operation, variable environments, and precise control—further in-depth research is still needed in the following directions:

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First, future work should develop an environmental feedback control loop. Current strategies are based on static assumptions and cannot dynamically respond to changes in temperature, humidity, pressure, or airflow. Building a closed-loop system that integrates environmental sensing, data prediction, and adaptive parameter adjustment will improve system robustness and enable stable performance in rapidly changing conditions.

Second, battery performance remains a key limitation in long-duration high-altitude use. Future research should investigate how different battery chemistries (e.g., $LiFePO_4$, manganese-based lithium cells) behave under low-pressure, low-temperature, and low-state-of-charge conditions. Modeling these effects will inform improved power management strategies.

Third, more comprehensive field trials are needed under extended and realistic plateau conditions. The current study focused on brief, one-time ascent testing. We recommend future field tests of at least seven days, capturing nighttime use, intense activity, and real respiratory patterns. These trials will help evaluate trigger accuracy, delay, and long-term system stability under complex physiological and environmental conditions.

5. Conclusion

Based on field testing at 7546 m and hypobaric chamber experiments, this study systematically evaluated the performance of a portable pulse oxygen concentrator under extreme high-altitude conditions and proposed feasible optimization strategies. The main findings are as follows:

- **Identified performance degradation trends:** Field data collected at five altitude points revealed that both oxygen concentration and pulse flow rate decreased with elevation. A sharp performance drop was observed above 6200 m, indicating that the device approaches its oxygen delivery limit in ultra-high-altitude conditions and requires targeted optimization.
- **Proposed lightweight optimization strategies and validated effectiveness:** Without modifying the device's core hardware, three control-level optimization strategies were designed and implemented. Chamber testing demonstrated significant improvements in oxygen output at simulated altitudes of 6000 m and 8000 m, confirming the practicality and effectiveness of the proposed approach.
- **Outlined future research directions:** Based on field-use scenarios, this study emphasized the need for an environment-responsive control loop, improved high-altitude power management, and extended field validation. These are key directions for future development of intelligent and robust oxygen systems.

These outcomes offer theoretical and engineering foundations for the design of portable oxygen systems in scenarios such as high-altitude healthcare, mountaineering, and field-based scientific research.

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