LIGHTHOUSE WORLDWIDE SOLUTIONS

TECHPAPER

# HVAC Energy Savings

## in Pharmaceutical and Semiconductor Cleanrooms


Authored by:
Jason Kelly


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# Overview

In today's rapidly evolving industrial landscape, energy efficiency in cleanroom environments is becoming increasingly critical, particularly within the pharmaceutical and semiconductor sectors. Cleanrooms, designed to maintain stringent air cleanliness standards, consume significantly more energy than traditional office spaces—often exceeding consumption by tenfold. This is primarily due to the high volumes of filtered and conditioned air required to meet specific cleanliness criteria. The HVAC systems in these facilities are responsible for a substantial portion of this energy use, with air movement fans alone accounting for up to 50% of total HVAC energy consumption. This introduction sets the stage for an insightful exploration of innovative strategies aimed at optimizing Air Change Rates (ACRs) and enhancing energy efficiency without compromising the essential cleanliness standards. By leveraging advanced technologies and real-time data, facilities can achieve remarkable energy savings while ensuring compliance with industry regulations, paving the way for more sustainable operational practices in cleanroom management.

*"leveraging advanced technologies and real-time data, facilities can achieve remarkable energy savings"*

The energy consumption of cleanrooms, which varies significantly in function and size, can exceed that of similarly sized offices by more than tenfold. A substantial amount of energy is necessary to supply large volumes of filtered and conditioned air to meet specific air cleanliness standards. Air movement fans alone can account for 35% to 50% of the HVAC energy consumption in cleanrooms, due to the power required to overcome the high-pressure differentials needed for high-efficiency filters and other circulation components. Consequently, the production of such high-quality air can consume up to 80% of the total energy used in a typical cleanroom manufacturing facility.

*HVAC Engineer testing air change rates*

Cleanrooms are energy-intensive environments due to the high Air Change Rates (ACRs) required to maintain strict cleanliness standards. This paper investigates strategies to optimize ACRs particularly in ISO 7 cleanrooms, using particle counters as feedback data loops to the Heating, Ventilation, and Air Conditioning (HVAC) system and Air Handling Units (AHUs) emphasizing that these cleanrooms are particularly well-suited for reductions in airflow rates due to the presence of separative devices like Laminar Airflow Cabinets (LAFs), Biological Safety Cabinets (BSCs), Isolators, and Restricted Barrier Access Systems (RABs). These devices operate independently with their own ISO 5 air supply, making ACR reductions less likely to compromise their environmental integrity.

Guided by ISO 14644-16, the paper explores how optimized HVAC operations, advanced filtration technologies, and practical operational adjustments can reduce energy consumption while maintaining compliance. Two key case studies—Lawrence Berkeley National Laboratory's work on Demand-Controlled Filtration (DCF) [2] and Research on energy demand reduction in pharmaceutical cleanrooms [3]—demonstrate that reducing ACRs can lead to significant energy savings without compromising cleanliness.

In cleanrooms, HVAC systems are designed to meet stringent environmental standards, controlling not only temperature and humidity but also airborne particle levels. The air quality in cleanrooms is maintained through HEPA or ULPA filters and constant air changes, which can make these systems energy intensive. Here are some common guidelines for different ISO classified cleanrooms and the relative air changes per hour that these cleanrooms and HVAC systems are designed to maintain and to ensure that room design to a particular ISO Classification is achieved.

In cleanroom HVAC design, the recommended air change rates (ACH) for different ISO classes according to ISO 14644-1:2015 are as follows:

- **ISO Class 8:** 10 to 20 ACH
- **ISO Class 7**: 30 to 65 ACH
- **ISO Class 6:** 80 to 150 ACH
- **ISO Class 5:** 200 to 450 ACH

These rates ensure that the cleanroom maintains the required level of air cleanliness by continuously filtering and circulating air to remove contaminants. If we look to ISO 7 Classified rooms the design criteria are between 30 to 60 ACH. HVAC design engineers typically set the ACH to 45 hitting the mid-range capacity of the AHU. This plays on a safe design where the AHU has additional capacity if needed. It is also important to understand that the size of cleanroom, type of equipment used in the cleanroom and the number of people permitted into the cleanroom all play a significant factor in determining the design of the HVAC system and AHU that will support such cleanrooms.  ISO 14644-16 has a good practical example of calculating air supply rates in non-unidirectional cleanrooms in Appendix A. that is recommended reviewing.

In the two case studies that this paper will present the key strategies in energy savings are mainly based on the three categories below:

- Fine-Tuning Air Change Rates (ACRs)
  - Adjusting ACRs based on particle concentrations allows for potential energy reductions.
  - Effective implementation requires precise and representative particle concentration measurements, which can be challenging in practice.
- Demand-Controlled Filtration (DCF)
  - Dynamically adjusting ventilation rates based on occupancy was highly effective in achieving energy efficiency.
  - DCF demonstrated substantial energy savings, up to 93.6% in case studies, with minimal impact on environmental cleanliness standards.
- Optimizing Airflow Patterns
  - Experimental setups showed that achieving high contaminant removal efficiency depended on proper airflow configurations.
  - The best results occurred when air was supplied directly above the product area without a diffuser and when air extraction grilles were positioned close to work areas.

### Key Findings

**Energy Savings:** DCF presented the highest energy-saving potential, especially in low-utilization cleanrooms.

**Environmental Compliance:** Adjusting ventilation rates based on occupancy or concentration levels-maintained cleanliness within regulatory requirements.

**Implementation Challenges:** Fine-tuning required accurate and real-time particle measurements, making it less practical compared to DCF.

## Fine-Tuning Air Change Rates

### Concept Overview

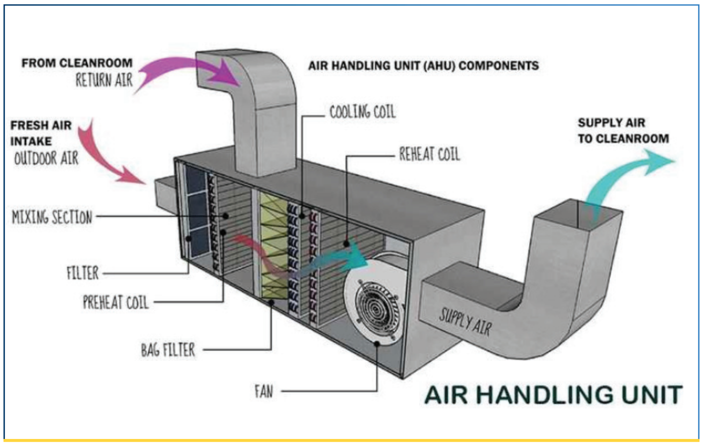
Fine-tuning Air Change Rates (ACRs) involves dynamically adjusting the airflow in cleanrooms based on real-time measurements of particle concentrations. This strategy allows facilities to maintain required cleanliness levels while reducing the energy consumption of HVAC systems, which typically represent a significant portion of operational costs in cleanrooms.

The potential energy savings from fine-tuning are substantial because ACRs are often overdesigned to ensure compliance with stringent cleanliness standards. Adjustments based on actual contamination levels can optimize airflow to match the room's operational needs, especially during periods of low activity.

### Achieving Fine-Tuning in Practice

**Accurate Particle Concentration Measurement**

Precise monitoring of particle concentrations is the cornerstone of this method. Advanced laser-based particle counters are typically employed for this purpose. These devices detect particles ≥0.3 μm and ≥0.5 μm in size, offering the resolution needed to make real-time adjustments.




*Air Handling Unit Diagram*

### Challenges:

**Sensor Placement:** Ensuring sensors capture representative data from the entire cleanroom is critical. Strategic placement near critical zones, such as workstations and airflow outlets, can provide accurate readings.

### Data Integration with HVAC Systems

Fine-tuning requires real-time integration of particle concentration data with HVAC control systems. Modern Building Management Systems (BMS) or Environmental Monitoring Systems (EMS) can process data from particle counters and automatically adjust airflow rates.

#### Implementation Steps:

**Baseline Mapping:** Establish baseline particle concentrations under different operational scenarios to identify thresholds for airflow adjustments.

**Dynamic Control Algorithms:** Use adaptive algorithms to increase or decrease airflow in response to deviations from cleanliness thresholds.

### Validation and Compliance

Adjustments to ACRs must be validated to ensure compliance with ISO standards, particularly ISO 14644-1 and ISO 14644-16. Validation involves particle monitoring, room recovery tests, and airflow pattern analyses to confirm that reduced ACRs do not compromise cleanliness. Microbial testing is also essential.

#### Recommended Tests:

- Particle Counting During Reduced Airflow: Verify that particle levels remain within acceptable limits.
- Smoke Studies: Visualize airflow patterns to ensure uniform coverage across the cleanroom.
- Microbial testing: Air samplers and settle plates positioned in key locations.

# Demand-Controlled Filtration (DCF)

## Concept Overview

Demand-Controlled Filtration (DCF) is an innovative HVAC strategy for cleanrooms, focusing on dynamically adjusting ventilation rates based on real-time occupancy and environmental conditions. By tailoring airflow to actual needs, DCF significantly reduces energy consumption while maintaining compliance with cleanliness standards. Case studies have shown significant energy savings, making DCF a highly effective approach for energy efficiency in cleanrooms.

## How DCF Works

### Core Principles

DCF systems rely on real-time data from sensors that monitor occupancy, particle concentrations, and environmental conditions. These inputs are processed by control systems to dynamically adjust Air Change Rates (ACRs) and ventilation levels.

**Occupancy-Based Adjustments:** When the cleanroom is unoccupied or during periods of reduced activity, ventilation rates are scaled down to save energy.

**Environmental Feedback Loops:** Particle counters ensure that cleanliness remains within acceptable thresholds during reduced airflow. If particle concentrations rise, the system can increase airflow rates temporarily to restore compliance.

## Components of a DCF System

1. **Occupancy Sensors:** Track the presence and movement of personnel within the cleanroom to signal the system when ventilation can be reduced.
2. **Particle Counters:** Provide real-time data on airborne particle levels to ensure cleanliness standards are met.
3. **Environmental Monitoring Systems (EMS):** Aggregate data from various sensors and use predictive algorithms to control HVAC systems dynamically.
4. **Variable Air Volume (VAV) Systems:** Enable precise adjustments to airflow rates in response to changes in demand.
5. **Restricted Room Access:** By restricting room access with magnetic locks that are activated during downtimes ensure rooms remain undisturbed during reduced air change rates.

### Optimizing Airflow Patterns

Optimizing airflow patterns is crucial for achieving high contaminant removal efficiency in cleanrooms. Experimental setups demonstrate that proper airflow configuration can enhance contaminant control while reducing energy consumption. Specifically, results indicate that the best outcomes are achieved when:

- Air is supplied directly above the product area without a diffuser.
- Air extraction grilles are strategically positioned close to work areas.

This approach ensures uniform airflow across critical zones, minimizing turbulence and optimizing contaminant removal efficiency.

## Implementation Steps

1. **Pre-Implementation Assessment**

- **Data Collection:** Conduct baseline studies to determine typical occupancy patterns and particle concentrations during various activities.
- **Feasibility Analysis:** Evaluate whether DCF is suitable based on the cleanroom's usage, classification, and existing HVAC infrastructure.

2. **System Design and Integration**

- **Sensor Placement:** Strategically place occupancy and particle sensors to ensure comprehensive data coverage.
- **Control Algorithm Development:** Use historical and real-time data to develop algorithms for dynamic airflow adjustments.
- **Retrofitting or Upgrading HVAC Systems:** Install VAV systems or other hardware to enable dynamic control.

3. **Testing and Validation**

- **Baseline Comparison:** Test the system under controlled conditions to compare energy consumption and cleanliness before and after DCF implementation.
- **Environmental Compliance:** Validate that reduced ventilation rates maintain compliance with ISO standards and other regulatory requirements.

# Case Study I:

## Energy Savings in a Class 100 Cleanroom Using Demand-Controlled Filtration

*Semiconductor Wire bonding process in a Class 100 cleanroom*

### Overview

The Lawrence Berkeley National Laboratory conducted a study on a Class M3.5 (Class 100) cleanroom to explore energy savings achieved through Demand-Controlled Filtration (DCF). This cleanroom, primarily used for silicon detector fabrication, demonstrated significant reductions in energy consumption by dynamically adjusting airflow based on real-time particle concentrations.

### Facility Description

**Size and Usage:** The cleanroom had a floor area of 28 $m^2$ (300 $ft^2$) and was used 2–4 times per week for 1–4 hours per day, with a maximum weekly usage of 13.5 hours.

**Design:** Airflow was recirculated via four variable frequency drive (VFD) fans and passed through HEPA filters covering the ceiling. Air was returned via grilles located near the floor.

## Control Strategies

Three fan control strategies were tested:

### 1. Preexisting Control:

- Maintained a constant pressure drop across HEPA filters.
- Fan speeds varied between 72–75% during the day and 58–67% at night.
- Resulted in limited energy savings.

### 2. Ten Percent Incremental Control:

- Fan speeds increased by 10% when particle concentrations exceeded a high limit.
- Speeds were reduced by 0.13% when particle levels fell below a low limit.

### 3. Proportional Control:

- Fan speeds were adjusted proportionally to the difference between measured and acceptable particle concentrations.
- Allowed rapid increases in fan speed (up to 70%) when needed and gradual decreases when particle concentrations were stable.

### Experimental Facilities, Instrumentation, and Procedures

#### Particle Counter:

- Used laser light scattering to measure particles ≥0.3 µm and ≥0.5 µm.
- A higher-resolution counter was introduced in later phases to improve particle detection.


*Remote particle counter w/ sample probe*

#### Data Acquisition System:

Automated control via an existing energy management system capable of updating fan speeds every second.


*Monitoring Software with Data Trending*

#### Phases:

- **Baseline:** Preexisting control strategy data collection.
- **DCF Phase 1:** Implemented the Ten Percent strategy.
- **DCF Phase 2:** Implemented the Proportional strategy with improved particle counter resolution.

# Results - Energy Savings

Energy savings were calculated using two baselines:

**Baseline 1:** Preexisting control strategy at 2.6 kW average power consumption.

**Baseline 2:** Assumed full-speed operation at 5.9 kW.

| Control Strategy | Energy Savings (%) |
|---|---|
| Preexisting | 10% (Baseline 1) |
| Ten Percent | 64% (Baseline 1), 84% (Baseline 2) |
| Proportional | 64% (Baseline 1), 84% (Baseline 2) |

**Energy savings from DCF ranged from 60–84%, with higher savings realized during unoccupied periods.**

### Particle Concentrations

The cleanroom maintained compliance with Class 100 standards 98% of the time during DCF operation.

Excursions above acceptable levels were rare, occurring fewer than 10 minutes per day. Adjustments to fan speeds quickly restored compliance.

### Industry Comments

Semiconductor manufacturers expressed concerns about particle control variability but recognized the potential for substantial savings.

The DCF system was deemed most suitable for smaller cleanrooms with limited and intermittent use.

## Conclusions Case Study I

This study demonstrated that DCF can significantly reduce energy consumption in Class 100 cleanrooms while maintaining compliance with stringent particle standards. The findings support the implementation of DCF in smaller cleanrooms and highlight the need for further research into optimizing DCF for larger, high-usage facilities.

# Case Study II:

## Energy Demand Reduction in Pharmaceutical Cleanrooms

*ISO 7 Pharmaceutical Cleanroom with separative devices*

## Overview

This case study examines two pharmaceutical cleanrooms where ventilation energy savings were achieved by optimizing Air Change Rates (ACRs), implementing Demand-Controlled Filtration (DCF), and improving ventilation efficiency. These facilities, located in the Netherlands, were monitored and simulated to quantify potential savings and ensure compliance with Good Manufacturing Practice (GMP) standards.

## Facilities and Instrumentation

### Monitored Cleanrooms

**Case Study H** (Hospital Pharmaceutical Facility):

- Room I: 30.6 $m^3$ volume, GMP B, 42 ACH.
- Room II: 65.1 $m^3$ volume, GMP C, 21 ACH.

**Case Study R** (Radioactive Pharmaceutical Facility):

- Volume: 192 $m^3$, GMP C, 20 ACH.

### Instrumentation and Monitoring

**Particle Counters:** Used to measure particle concentrations (≥0.5 μm) at multiple positions within each cleanroom.

**Occupancy Sensors:** Tracked personnel entry and presence.

**Simulations:** Developed using ordinary differential equations to model particle concentration under various airflow conditions.

## Control Strategies

**Fine-Tuning:** ACR adjusted based on particle concentrations.

**Demand-Controlled Filtration (DCF):** ACR reduced during unoccupied periods, with a minimum threshold to maintain pressure hierarchy.

## Experimental Procedures

### Fine-Tuning

Simulations suggested that ACRs could be reduced by a factor of 10 in some cases while maintaining GMP compliance. For example, in Room II of Case Study H, the ACR was reduced from 21 ACH to 2.1 ACH during simulations.

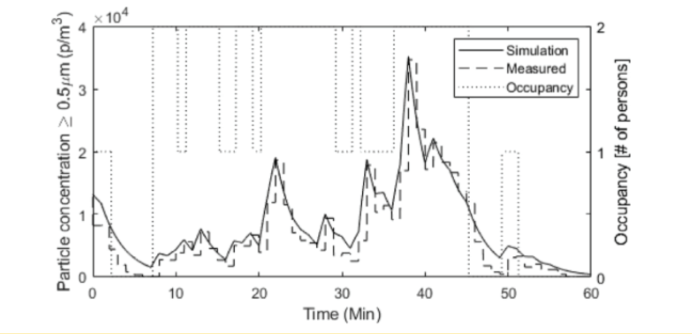
### DCF Implementation

#### ACRs were reduced based on occupancy:

- **Occupied:** Maintained standard ACR (e.g., 21 ACH).
- **Unoccupied:** Reduced to 6 ACH after 30 minutes of no activity.

### Ventilation Efficiency

Airflow patterns were studied in a controlled cleanroom environment with different configurations of air supply and extraction.




*Sample result from the validation study, with time (in minutes) on the x-axis. The left y-axis indicates the particle concentration (p/m3) for particles ≥0.5 μm and the right y-axis presents the occupancy level in number of persons. Shown measurement and occupancy data have been taken from Case study H (Room II) from 15:30–16:30 (September 22nd, 2016)*

## Results - Energy Savings

| Cleanroom | Occupied time (%) | ACR Setback (%) | Fan Energy Savings (%) |
|---|---|---|---|
| **Case Study H:** Room 1 | 1.8% | 96.1% | 93.6% |
| **Case Study H:** Room 2 | 3.2% | 88.9% | 86.8% |
| **Case Study R** | 22.5% | 70.0% | 68.1% |

### Particle Concentrations

All rooms-maintained compliance with GMP B or C standards.

Particle concentrations remained low during unoccupied periods, reaching near-zero levels with reduced airflow.

### Ventilation Efficiency Improvements

**Swirl Diffusers:** Achieved a high contaminant removal efficiency (ε = 1.83 in the best-case configuration).

**Localized Ventilation:** Improved efficiency by aligning supply and extraction near contamination sources and work areas.

## Discussion

### Challenges and Considerations

1. **Occupancy-Driven ACR Adjustments:** Effective in low-utilization facilities but may not suit high-throughput operations.
2. **System Delays:** ACR changes took up to 150 seconds to stabilize, impacting immediate particle removal.
3. **Fine-Tuning Limitations:** Less reliable due to potential overshooting of particle limits during rapid activity changes.

### Industry Implications

The study highlights the need for:

- **Standardized Guidelines:** To support dynamic airflow adjustments.
- **Advanced Monitoring Systems:** For real-time particle and occupancy tracking.

## Conclusions Case Study II

This case study demonstrates that pharmaceutical ISO 7 cleanrooms can achieve significant energy savings without compromising cleanliness by using advanced ventilation strategies and particle monitoring systems. Demand-Controlled Filtration emerged as the most practical and effective solution, offering up to 93.6% fan energy savings in low-utilization settings. Combining DCF with localized ventilation strategies can further enhance efficiency and reduce costs, making cleanrooms more sustainable while maintaining GMP compliance.

## Summary

Cleanrooms are essential for maintaining the strict environmental conditions required in industries such as pharmaceuticals, biotechnology, and electronics. However, they are among the most energy-intensive environments, often consuming over ten times more energy than similarly sized office spaces. This is largely due to the high energy demands of HVAC systems, which are critical for maintaining air quality, temperature, and pressure. Implementing strategies to reduce energy consumption—such as optimizing air changes per hour (ACRs) and dynamically adjusting HVAC operation—offers significant benefits for both environmental sustainability and operational cost savings.

## The Case for Reducing Air Changes Per Hour (ACRs)

### Energy Consumption in HVAC Systems:

HVAC systems account for up to 80% of a cleanroom's total energy use, with fans alone consuming 35% to 50% of this energy to overcome pressure differentials in high-efficiency filters. Reducing ACRs—while still adhering to cleanliness standards—can drastically lower this demand, enabling significant energy savings.

### Supporting Standards and Guidelines:

ISO 14644-16 provides a structured framework for optimizing energy efficiency in cleanrooms. It emphasizes the safe reduction of ACRs through systematic assessment, validation, and the use of advanced monitoring systems. These guidelines ensure that energy savings are achieved without compromising environmental integrity or regulatory compliance.

### Validated Approaches:

Studies, such as those conducted by the Lawrence Berkeley National Laboratory and other researchers, have shown that reducing ACRs through methods like Demand-Controlled Filtration (DCF) can yield energy savings of up to 93.6%. These findings are supported by case studies in pharmaceutical and electronics cleanrooms, where lower ACRs maintained cleanliness standards while significantly reducing HVAC energy use.

## Benefits for Companies

**Cost Savings:**

- Lower HVAC energy consumption translates directly into reduced operational costs.
- Case studies show annual savings of up to $200,000 for facilities that implement optimized ACR strategies.

**Environmental Sustainability:**

- Reducing HVAC energy use lowers the carbon footprint of cleanroom operations, aligning with global sustainability goals and corporate environmental responsibility initiatives.
- Dynamic airflow adjustments during low-occupancy periods further reduce unnecessary energy waste.

**Improved System Longevity:**

Operating HVAC systems at lower intensities reduces wear on components, decreasing maintenance costs and extending system lifespan.

**Regulatory Compliance:**

- Advances in particle counting and real-time monitoring ensure that cleanliness standards are maintained even with reduced airflow.
- ISO 14644-16 provides validation methods, such as room recovery tests and particle monitoring, to maintain compliance while achieving energy efficiency.

# Conclusion

Adopting energy reduction strategies in cleanrooms is not just an operational improvement—it's a competitive advantage. Rising energy costs and increasing regulatory focus on sustainability make this an opportune time for companies to act. With proven methodologies, advanced technologies, and supportive standards in place, reducing ACRs offers a clear pathway to achieving both financial and environmental benefits.

By focusing on smarter HVAC operation and leveraging validated strategies like DCF and airflow pattern optimization, companies can enhance operational efficiency, reduce energy footprints, and secure long-term cost savings—all while maintaining the highest standards of cleanroom performance.

If you would like more information on how we can help you achieve the results shown here, visit our **Consultancy Services page.**

## References


1. ISO 14644-16:2019 Energy efficiency in cleanrooms and separative devices
2. Energy Savings in Cleanrooms from Demand-Controlled Filtration. David Faulkner, William J. Fisk, and John T. Walton. (Sept 2016) - Publication #: LBNL-38869
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golighthouse.com

info@golighthouse.com

LIGHTHOUSE WORLDWIDE SOLUTIONS

(Toll-free) 1 800 945 5905

(International) +1 541 770 5905