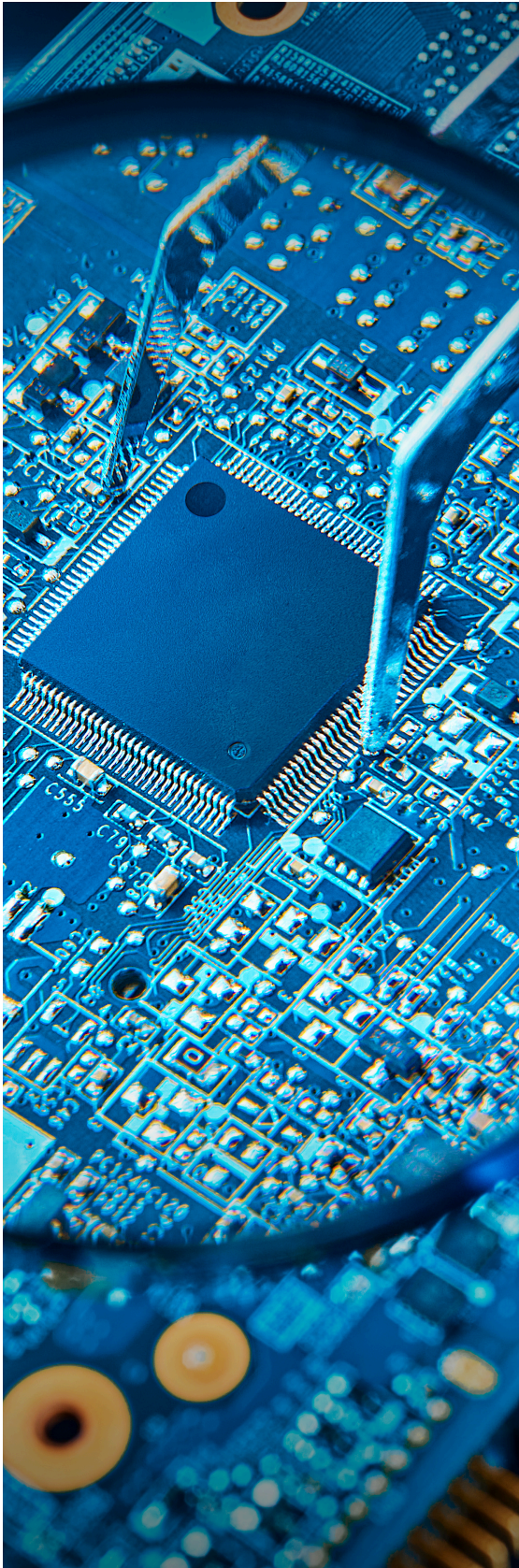




A Practical Refrigerant Approach for Semiconductor, Laboratory, and Life Science Applications

Precision process cooling is increasingly required to deliver two objectives at the same time: dependable thermal performance for critical equipment and a credible route towards lower environmental impact. For semiconductor, laboratory, and life science users, refrigerant selection therefore cannot be reduced to global warming potential or safety classification alone.

R290, refrigerant-grade propane, is a natural, non-fluorinated refrigerant with extremely low global warming potential. When a chiller is engineered specifically around its A3 characteristics, R290 can provide a practical basis for compact precision cooling while retaining the thermal, hydraulic, and operational characteristics required by demanding applications.

CO₂ (R744) is another important natural refrigerant option and offers clear environmental and non-flammability advantages. However, CO₂ systems operate within a substantially different pressure regime. As ambient temperature rises, pressure management, heat rejection, and control strategy become increasingly important system design considerations. The appropriate comparison is therefore not simply R290 versus CO₂ by refrigerant classification, but the performance, reliability, serviceability, and safety of the complete cooling architecture across the application's full operating envelope.

ATC's approach is to assess refrigerant technology alongside cooling duty, coolant temperature, stability, flow, pressure, ambient conditions, installation, EHS requirements, certification, and lifetime service needs. This paper explores that approach and considers where R290 can provide a compelling alternative alongside CO₂ and other low-GWP refrigerant technologies.

Precision Cooling is a Process Requirement

Semiconductor manufacturing, laboratory instrumentation, and life science equipment all include applications where temperature stability, repeatability, and uptime can directly affect the performance of the wider system. Unlike comfort cooling, a recirculating chiller forms an integral part of the process it supports.

Typical applications include semiconductor fabrication processes such as ion implantation, etching and deposition, metrology and inspection equipment, lasers and optics, analytical and scientific instrumentation, laboratory and life science equipment, and other temperature-sensitive manufacturing processes.

Although individual applications differ, the chiller may be required to satisfy a combination of cooling capacity, process fluid temperature, temperature stability, ambient operating range, fluid compatibility, flow and pressure, variable heat load, continuous operation, communications, installation, and EHS requirements.

A low-GWP refrigerant must therefore still enable the chiller to deliver the required thermal and hydraulic performance. For critical process equipment, reliability and performance across the complete specified operating envelope must be considered alongside refrigerant GWP.

Why Refrigerant Choice is Changing

Many established process chillers have historically used fluorinated refrigerants because they provide a proven combination of performance, stability, and manageable safety characteristics. However, the global phasedown of higher-GWP HFCs, together with increasingly restrictive regional regulation, is changing the refrigerant landscape.

For equipment with a long commercial and operational life, refrigerant selection is also a question of future resilience. A cooling platform developed solely around what is permitted today may become increasingly exposed to changes in refrigerant availability, regulatory requirements, and servicing considerations during the lifetime of the equipment.

This is particularly relevant to OEMs developing equipment platforms that may take several years to design, validate, and qualify before remaining in production and service for many more.

The challenge is therefore not simply to select a refrigerant with a lower GWP. It is to identify a refrigeration technology that can reduce environmental impact without compromising process performance, reliability, safety, serviceability, or the expected operating life of the equipment.



Why R290?

R290 is refrigerant-grade propane. Its principal environmental advantage is its extremely low global warming potential and its status as a non-fluorinated refrigerant.

- Extremely low refrigerant GWP
- No reliance on HFC quota availability
- Established thermodynamic properties
- Potential for efficient refrigeration system design
- Low direct climate impact in the event of refrigerant loss
- Potential long-term resilience as restrictions on fluorinated refrigerants increase

For semiconductor manufacturers, laboratories, and life science organisations pursuing sustainability objectives, these characteristics are attractive. Importantly, R290 can also form the basis of compact precision cooling equipment using a comparatively familiar vapour-compression architecture.

R290 is, however, an A3 refrigerant. Its suitability therefore depends on the way the complete equipment and installation are engineered around that characteristic.



Understanding the A3 Classification

Refrigerant safety classifications consider toxicity and flammability. R290 is classified A3: lower toxicity ('A') and higher flammability ('3').

The presence of an A3 refrigerant does not, by itself, determine whether a chiller is suitable. An appropriate assessment considers:

- Refrigerant quantity and circuit construction
- Potential leak scenarios and possible ignition sources
- Electrical component design and positioning
- Enclosure design, airflow, and ventilation
- Installation environment
- Servicing procedures
- Applicable equipment standards, local codes, and regulations
- The end user's own EHS requirements

The practical engineering question therefore moves beyond simply *"Is propane flammable?"* to *"How has the equipment and its installation been designed to manage the characteristics and potential risks associated with the refrigerant?"*.

Refrigerant Charge and Risk Management

When using a flammable refrigerant, refrigerant inventory is an important part of the design assessment. A smaller charge limits the quantity potentially available in a release scenario, but charge should not be treated as the sole safety measure.

Circuit integrity, component selection, ignition-source management, enclosure design, airflow, ventilation, service access, and the intended installation environment need to be considered together. Applicable equipment standards can also distinguish between systems according to refrigerant charge and intended use.

Minimising refrigerant charge is therefore one element of a broader engineering approach to managing R290. For example, ATC has developed compact R290 configurations using approximately 95g of refrigerant, demonstrating how low refrigerant inventory can be incorporated into a practical precision cooling platform.

Engineering for R290

Successful adoption of R290 requires a system designed around the refrigerant rather than a simple substitution into a legacy refrigeration circuit.

Depending on the product and applicable standards, the engineering assessment can include refrigeration circuit integrity, minimised charge, potential ignition sources, electrical component location, airflow, ventilation, leak behaviour, controls, shutdown strategy, service access, and maintenance procedures.

For the ATC G Series, internal airflow is an important part of the design approach. In the event of a refrigerant release, the airflow is designed to disperse and dilute the released gas rapidly, rather than allow it to accumulate within the enclosure, reducing the potential for a flammable concentration to develop.

Why Ambient Operating Conditions Matter

Ambient temperature is a critical but sometimes under-emphasised part of process chiller specification. A chiller has to reject the process heat together with energy introduced by the refrigeration cycle into its surroundings. As ambient temperature rises, heat rejection becomes more demanding.

The effect depends on the refrigerant, condenser design, compressor selection, airflow, refrigeration architecture, and control strategy. The meaningful specification is therefore not simply nominal cooling capacity, but the cooling capacity and process stability that can be maintained at the required process fluid temperature and maximum specified ambient condition.

This is particularly important where chillers operate continuously, are integrated within larger equipment, are installed in restricted spaces, or experience elevated local ambient temperatures. Process cooling equipment should therefore be assessed across its complete operating envelope rather than at a single favourable nominal condition.

Demonstrated R290 Performance Across the Operating Envelope

Refrigerant selection alone does not determine high-ambient performance. System architecture, condenser sizing, airflow, compressor selection, and control strategy all contribute to the usable operating envelope of the process chiller.

ATC has characterised its G01 R290 platform across different ambient temperatures, process temperatures, and airflow configurations. Testing at 30°C ambient with the high-speed fan configuration demonstrated approximately 750W of cooling capacity at a process temperature of 6.8°C, 1000W at 23.6°C, and 1,250W at 38.6°C.

At 20°C ambient, further testing demonstrates how system configuration can be used to optimise the available cooling capacity, with the high-speed fan configuration achieving approximately 2kW at a 30°C process temperature.

These results demonstrate that an R290 system can be engineered to provide a measured and predictable cooling envelope across changing ambient and process conditions. For precision process cooling, this is more meaningful than assessing refrigerant choice solely on GWP or refrigerant type.

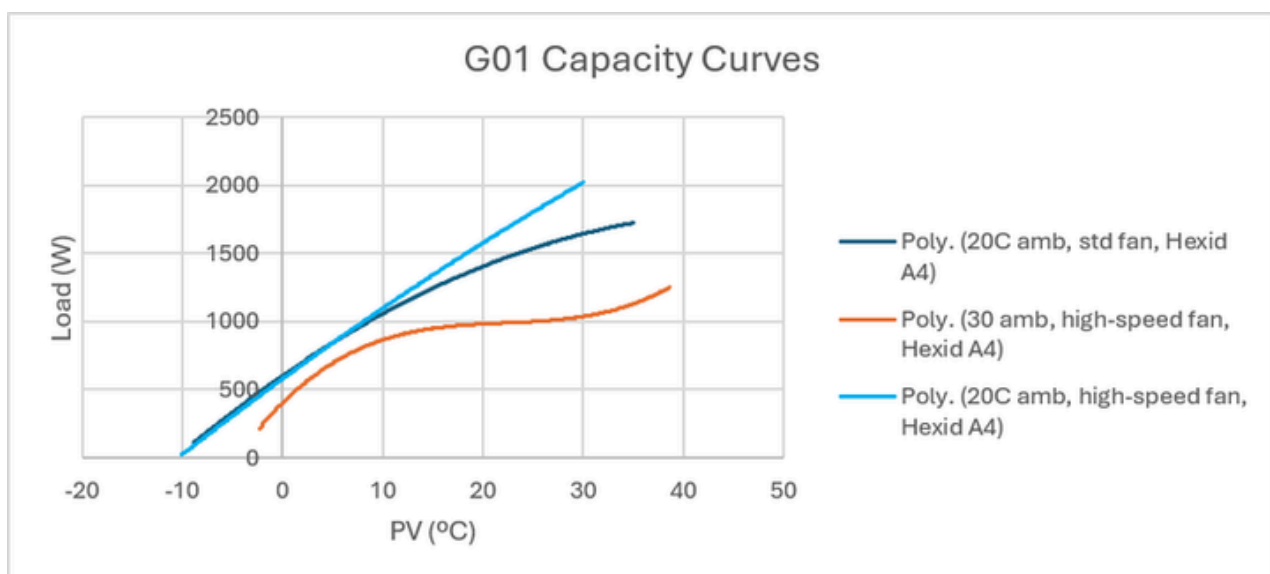


Figure 1 - G01 R290 Measured Cooling Capacity Across Ambient Conditions

These results do not imply that R290 inherently outperforms CO₂ at elevated ambient conditions. Rather, they demonstrate that R290 can provide a characterised operating envelope without the very high refrigerant-side pressures associated with CO₂. The comparison between the two technologies should therefore consider whole-system performance, pressure management, complexity, serviceability, and application requirements, rather than refrigerant GWP alone.

R290 and CO₂ - Two Different Natural Refrigerant Approaches

CO₂ (R744) is another natural refrigerant attracting interest in process cooling. It offers extremely low GWP and a non-flammable classification. These are important advantages, but R290 and CO₂ should not be treated as interchangeable simply because both have very low GWP.

CO₂ refrigeration operates at substantially higher pressures than conventional refrigeration architectures. System architecture, component selection, pressure management, and control strategy therefore become important design considerations. Ambient conditions can also be particularly relevant to system pressure and heat-rejection behaviour, depending on the CO₂ architecture employed.

This does not make CO₂ inherently unsuitable for process cooling. It means that customers should compare the complete system rather than refrigerant headline characteristics alone.

When evaluating R290 and CO₂ platforms, relevant questions include:

- What cooling duty is maintained at maximum specified ambient?
- What happens to system operating pressures as ambient temperature increases?
- How are those pressures controlled and protected?
- Is cooling capacity derated at higher ambient temperatures?
- What temperature stability is maintained across the operating envelope?
- What pressure-rated components and safeguards are required?
- How complex is the system to service and maintain?
- What skills and equipment are required by service personnel?
- What is the expected lifetime operating and maintenance profile?

For applications requiring reliable, repeatable process cooling across a broad ambient envelope, these questions are important. R290 can provide an attractive alternative where extremely low GWP is required alongside a comparatively conventional vapour-compression architecture, provided its A3 characteristics are appropriately addressed.

The comparison should therefore move beyond “R290 is flammable” and “CO₂ is non-flammable” to a more useful question: *Which refrigeration architecture provides the required combination of safety, cooling performance, temperature stability, ambient capability, reliability, serviceability, and lifetime operational performance for the application?*



Semiconductor EHS Requirements

Semiconductor manufacturing equipment is commonly subject to extensive EHS assessment. SEMI S2 provides a widely recognised framework for environmental, health, and safety considerations associated with semiconductor manufacturing equipment.

For an R290 chiller, the relevant question is how the cooling system fits within the risk assessment and EHS requirements applying to the wider tool and facility. Individual manufacturers and OEMs may impose requirements beyond regulatory or industry-standard minimums.

Semiconductor manufacturers are increasingly considering natural, extremely low-GWP technologies as part of their longer-term refrigerant strategy. For R290 applications, appropriate consideration of the refrigerant's A3 characteristics can be incorporated into the equipment and installation risk assessment, alongside the customer's own EHS requirements. Early engagement between the chiller manufacturer, equipment OEM and customer EHS team can ensure these requirements are addressed as part of the development and qualification process.



Regulatory Landscape and Regional Considerations

The transition away from higher-GWP refrigerants is not simply a future policy direction. In several major markets, restrictions are already taking effect, with further changes scheduled over the next few years. For equipment manufacturers and OEMs supplying internationally, refrigerant choice therefore needs to be considered not only against today's application requirements, but also against the regulatory environment that the equipment is likely to encounter during its operating life.

European Union

The European Union has introduced a significantly more restrictive F-gas framework under Regulation (EU) 2024/573. For stationary chillers with a rated capacity up to and including 12kW, the placing on the market of new equipment containing or relying upon fluorinated greenhouse gases with a GWP of 150 or more is prohibited from 1st January 2027, except where the refrigerant is required to meet safety requirements at the site of operation.

For stationary chillers above 12kW, fluorinated greenhouse gases with a GWP of 750 or more are prohibited in new equipment from the same date, again subject to the specified safety exception. The regulation moves further for smaller chillers: from 1st January 2032, stationary chillers up to and including 12kW will generally be prohibited from using fluorinated greenhouse gases at all, unless required to meet safety requirements at the site of operation.

This is particularly relevant to compact laboratory, life science, and process chillers, many of which fall within the sub-12kW category. For equipment expected to remain in service for a number of years, refrigerant choice therefore becomes more than a question of today's compliance; it becomes part of the equipment's longer-term product strategy. As a non-fluorinated refrigerant with extremely low GWP, R290 therefore provides one potential route for OEMs seeking greater long-term resilience as restrictions on fluorinated refrigerants increase.

A Specific Semiconductor Consideration in the EU

The semiconductor sector has received specific temporary recognition under Commission Implementing Regulation (EU) 2026/286, which provides an exemption from certain 2027 stationary chiller restrictions for qualifying equipment used to support semiconductor manufacturing.

The exemption provides a transitional period for specified semiconductor chiller applications, subject to the conditions and labelling requirements of the Regulation.

Importantly, the exemption should be viewed as transition time rather than a reversal of regulatory direction. For semiconductor OEMs developing equipment with lengthy design, validation, and qualification cycles, this creates an opportunity to evaluate alternative refrigeration technologies before the end of the transitional period.



United States

The United States is implementing HFC technology-transition requirements under the American Innovation and Manufacturing (AIM) Act, through the US Environmental Protection Agency's Technology Transitions programme. Rather than applying a single refrigerant prohibition, the framework establishes GWP limits and compliance dates according to equipment sector and application.

For stand-alone chillers used for industrial process refrigeration with an exiting fluid temperature of -30°C or above, the EPA specifies a maximum refrigerant GWP of 700 from 1st January 2026. For stand-alone chillers with an exiting fluid temperature from -50°C to below -30°C , the same GWP 700 limit applies from 1st January 2028.

Semiconductor manufacturing equipment receives specific treatment. For stand-alone industrial process refrigeration chillers used in semiconductor manufacturing equipment, with a refrigerant charge of 100lb or less and an exiting fluid temperature of -50°C or above, the EPA specifies a maximum GWP of 700 from 1st January 2030.

For semiconductor OEMs, this provides additional transition time compared with some general industrial process applications. However, equipment platforms can take several years to design, validate, and qualify, and may then remain in production and service for considerably longer. The US timetable therefore reinforces the value of evaluating lower-GWP and natural refrigerant technologies as part of the next product development cycle rather than treating refrigerant transition solely as a future compliance exercise.



Great Britain

Great Britain operates under its own F-gas framework and should not be assumed to follow the European Union's regulatory timetable.

In May 2026, Defra confirmed that, following consultation on reform of the HFC phase-down, the UK Government would not legislate during 2026 to change the phase-down steps applying from 1st January 2027. The existing GB HFC phase-down step therefore continues to apply for 2027.

The UK Government has nevertheless stated that it remains committed to further reform of the HFC phase-down. The longer-term direction therefore remains towards reduced dependence on higher-GWP HFCs, although the current timetable differs from that of the European Union.

For OEMs supplying equipment into both Great Britain and the EU, this distinction is important. Refrigerant compliance should be assessed according to the market in which the equipment is being placed on the market, rather than assuming a common European timetable.

What This Means for Equipment Selection

Across the EU and US in particular, regulatory change is increasingly moving refrigerant choice from a component-level decision into a product platform decision. For semiconductor, laboratory, and life science OEMs, the practical question is no longer simply “Which refrigerant can we use today?” It is increasingly, “Which refrigerant technology can provide the required performance, safety, and serviceability, while remaining viable across the expected commercial life of the equipment?”.

R290 is relevant within this discussion because it combines extremely low GWP with a non-fluorinated refrigerant platform, providing a potential route towards greater long-term resilience as restrictions on higher-GWP fluorinated refrigerants increase.

Its A3 characteristics require appropriate consideration of installation conditions, EHS requirements, applicable standards, and application performance, all of which can be addressed as part of the overall system design and application assessment. Where these requirements are appropriately engineered and managed, R290 provides a credible and compelling option for OEMs seeking to combine precision process performance with a longer-term refrigerant strategy.



Regulatory Sources

- Regulation (EU) 2024/573, Annex IV, stationary chiller restrictions
- Commission Implementing Regulation (EU) 2026/286, semiconductor chiller exemption
- US EPA Technology Transitions - HFC Restrictions by Sector
- UK Department for Environment, Food, & Rural Affairs - Amending the hydrofluorocarbon phasedown schedule, update 15th May 2026

Choosing Between R290, CO₂, and Low-GWP Fluorinated Refrigerants

There is unlikely to be one refrigerant technology that is optimal for every process cooling application.

R290

R290 offers extremely low GWP, a non-fluorinated refrigerant platform, and a comparatively conventional vapour-compression architecture. Its A3 characteristics can be addressed through appropriate product engineering, installation assessment, and consideration of customer EHS requirements.



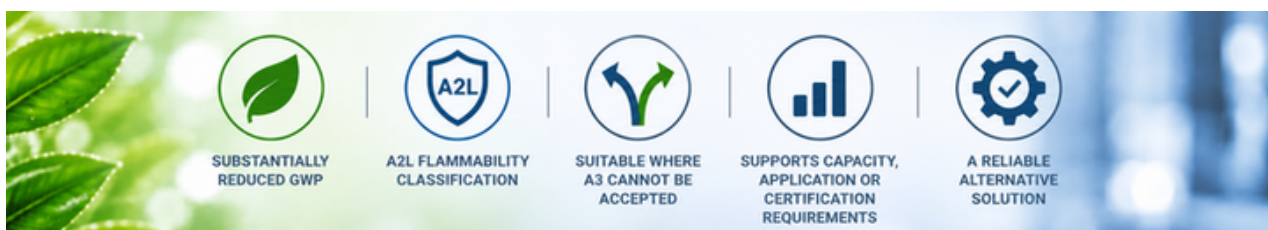
CO₂/R744

CO₂ offers extremely low GWP and non-flammable characteristics. Its substantially different operating pressure regime means that pressure management, ambient conditions, controls, component selection, and service requirements form important parts of the application assessment.



Low-GWP Fluorinated Alternatives

Refrigerants such as R454C can provide substantially reduced GWP while carrying an A2L rather than A3 flammability classification. Such platforms may be appropriate where an A3 refrigerant cannot be accepted or where capacity, application, or certification requirements point towards an alternative solution.



The appropriate technology should be selected against cooling capacity, process temperature, stability, ambient range, hydraulic requirements, refrigerant charge, installation, EHS policy, legislation, certification, reliability, serviceability, and expected equipment life.

Looking Beyond Refrigerant GWP

The environmental impact of precision process cooling extends beyond refrigerant GWP. Energy consumption, refrigerant charge, leakage prevention, equipment lifetime, reliability, serviceability, repairability, and responsible end-of-life refrigerant recovery all contribute to the overall environmental performance of a cooling system.

This is particularly important for process equipment that may operate continuously and remain in service for many years. A refrigeration technology with an extremely low refrigerant GWP is not automatically the most sustainable lifetime solution if it introduces unnecessary complexity, consumes significantly more energy, is difficult to maintain, or contributes to premature equipment replacement.

Refrigerant GWP should therefore form part of a whole-system and whole-life assessment, considered alongside energy efficiency, operational performance, reliability, maintainability, and equipment longevity.

ATC's Approach to Precision Process Cooling

Applied Thermal Control develops recirculating cooling systems for applications where temperature control, reliability, and integration are critical. ATC's approach is to assess the complete application requirement, rather than treating refrigerant selection as an isolated environmental decision.

Application assessment considers cooling duty, process fluid temperature, temperature stability, ambient operating conditions, flow and pressure requirements, process fluid compatibility, communications, installation conditions, regional compliance, EHS requirements, and lifetime service needs.

For suitable applications, ATC's G-Series R290 platform provides a natural refrigerant route to extremely low-GWP precision process cooling. Its A3 characteristics can be addressed through appropriate system design, application assessment, and consideration of installation and customer EHS requirements.

ATC's application-led approach allows the refrigeration architecture to be selected around the requirements of the process, with R290 providing a compelling option where extremely low GWP, precision cooling performance and long-term refrigerant strategy are key considerations.



The transition towards lower-impact precision process cooling is about considerably more than replacing one refrigerant with another.

For semiconductor, laboratory, and life-science applications, R290 should be considered as a credible engineering option for precision process cooling. Its extremely low GWP and non-fluorinated nature provide clear environmental advantages and make it relevant to OEMs developing their next generation of cooling platforms.

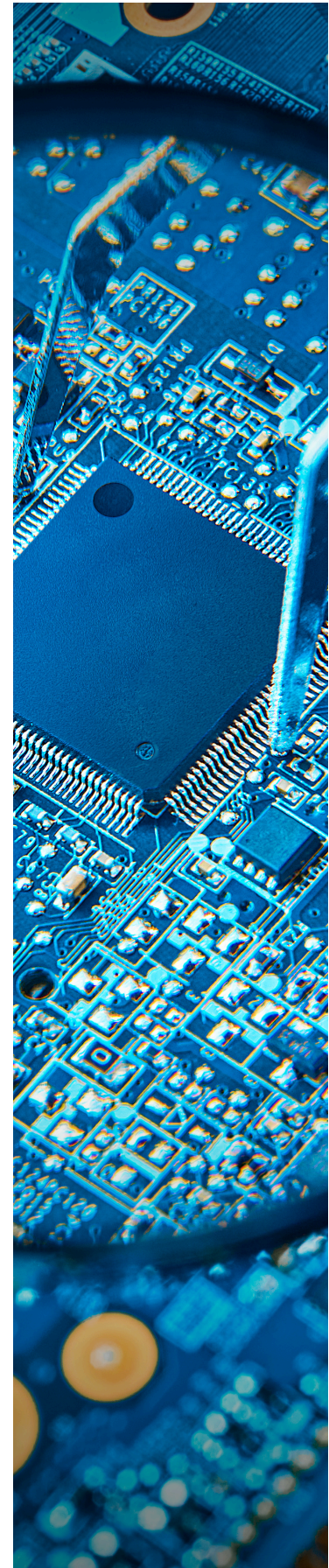
R290's A3 classification requires appropriate engineering and application assessment. However, flammability classification should be considered within the wider context of refrigerant charge, equipment construction, airflow, installation conditions, servicing, applicable standards, and end-user EHS requirements.

Other technologies, including CO₂ and low-GWP fluorinated refrigerants, will continue to provide appropriate solutions for many applications. Refrigerant selection should therefore not be based on GWP or safety classification alone.

Cooling capacity, temperature stability, hydraulic performance, operating pressures, ambient capability, refrigerant architecture, system complexity, reliability, serviceability, EHS requirements, and lifetime operational performance should all form part of the assessment.

For demanding process cooling applications, particularly where ambient conditions, uptime, serviceability, and long equipment life are important, the more useful question is not simply *"Which refrigerant has the lowest GWP?"* but rather *"Which cooling technology can reliably deliver the required process conditions throughout the complete operating envelope?"*

When assessed on that basis, R290 represents a compelling natural refrigerant option for precision process cooling. Its combination of extremely low GWP, established refrigeration principles, and the ability to engineer effectively around its A3 characteristics means it deserves serious consideration by semiconductor, laboratory, and life science OEMs evaluating their next generation of cooling platforms.



 +44 (0) 1530 83 99 98

 www.app-therm.com

 sales@app-therm.com

Case Study - Transitioning an Established Life-Science Application to R290

ATC was approached to develop a lower-GWP cooling solution for an established application used by a global life science equipment manufacturer. Compact recirculating chillers form an integral part of the customer's laboratory equipment, with defined requirements for cooling performance, low-temperature operation, hydraulic performance, and international deployment.

The Challenge

The objective was not simply to replace one refrigerant with another. The existing cooling platform already provided the thermal and hydraulic characteristics required by the wider equipment, meaning that any alternative needed to retain these functional requirements without forcing a fundamental redesign of the customer's application. The solution also needed to be suitable for repeatable production, rather than demonstrating R290 only through a one-off prototype.

Developing the R290 Solution

ATC used the established cooling requirement as the engineering baseline and developed a new G-Series configuration specifically around R290.

The resulting system provides approximately 1kW of process cooling capability while retaining the required low-temperature capability and application-specific hydraulic performance of the established platform.

Rather than treating R290 as a direct refrigerant substitution, the refrigerant system, controls, airflow, and overall chiller architecture were developed around the characteristics of an A3 refrigerant.

Managing R290 within the Chiller

The resulting configuration uses approximately 95g of R290. Minimising refrigerant inventory formed part of the overall design and risk-management approach while still delivering the required cooling performance.

Internal airflow also forms part of the system design. In a potential refrigerant release scenario, airflow is designed to disperse and dilute released R290 rather than allow it to accumulate within the enclosure, reducing the potential for a flammable concentration to develop.

These measures form part of the overall system-level approach to managing R290 and should be considered alongside the installation environment, applicable standards and end-user EHS requirements.

The Outcome

The development demonstrates that transitioning to an extremely low-GWP refrigerant does not necessarily require an OEM to sacrifice the thermal and hydraulic characteristics established with previous generations of cooling equipment.

Importantly, the resulting R290 solution is repeatable for ongoing production rather than being limited to a development prototype. It therefore provides a practical example of how R290 can be incorporated into an established precision cooling application while retaining the functional requirements of the wider environment.

Case Study - Transitioning an Established Life-Science Application to R290

Relevance to Semiconductor Process Cooling

Although this application was developed for life science equipment, many of the underlying engineering considerations are equally relevant to semiconductor process cooling, including stable thermal performance, defined hydraulic conditions, equipment uptime, EHS acceptance, and long-term environmental performance.

The case study demonstrates that R290 should not be viewed simply as an environmentally preferable refrigerant. While the complete cooling system is engineered around its characteristics, R290 can provide the basis for a practical and repeatable precision cooling platform.

For semiconductor OEMs evaluating natural refrigerant technologies, the appropriate comparison should therefore be between the complete cooling architectures. Refrigerant operating pressure, cooling performance, ambient capability, system complexity, EHS requirements, serviceability, and expected lifetime performance should all form part of that assessment.



Sources

- European Union – Regulation (EU) 2024/573 – F-gas requirements and stationary chiller prohibitions
- United States – US EPA – Technology Transitions HFC Restrictions by Sector
- Semiconductor EHS – SEMI S2 0724 – Environmental, Health and Safety Guideline for Semiconductor Manufacturing Equipment
- Equipment Safety – IEC 61010-2-011:2019 – Particular requirements for refrigerating equipment
- Great Britain – DEFRA – F-gas Regulation in Great Britain and HFC phase-down reform.