Socio-economic benefits from ESA's Science Core Technology Programme

A report for esa

CASE STUDY: Joule-Thomson Cryocooler

know.space

June 2022

Development of new long-life Joule-Thomson Cryocoolers …

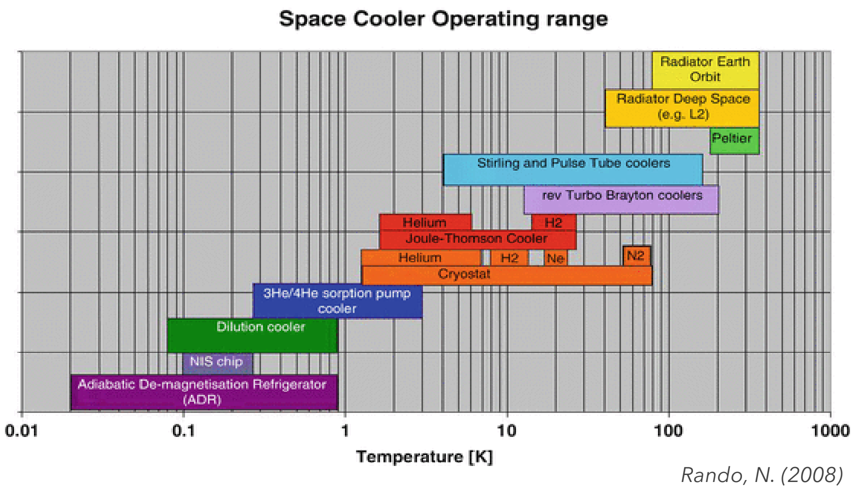
Cryocoolers are essential components in regulating the temperature of instruments and sensors onboard spacecraft to ensure **optimised performance** and **mission lifetime**.

Space cryogenics are used for focal plane cooling in:

- *Science missions* (e.g. black hole studies, gamma ray studies, cosmic microwave background radiation studies and chemistry of exoplanet studies);
- *Earth Observation missions* (e.g. imagery, monitoring of lands, meteorology, and Fatmospheric chemistry).

They have the potential to be applied to other future applications also, such as sample collection and conservation, high temperature superconductors, and in-situ resource utilisation.

Used since the beginning of space activities, cryogenics have seen many developments, notably in the US and Europe. Today, there exists a variety of cryocooling solutions, covering different sizes, masses, resource utilisation requirements, temperature ranges and lifetimes[1,2], as can be seen in the graph.

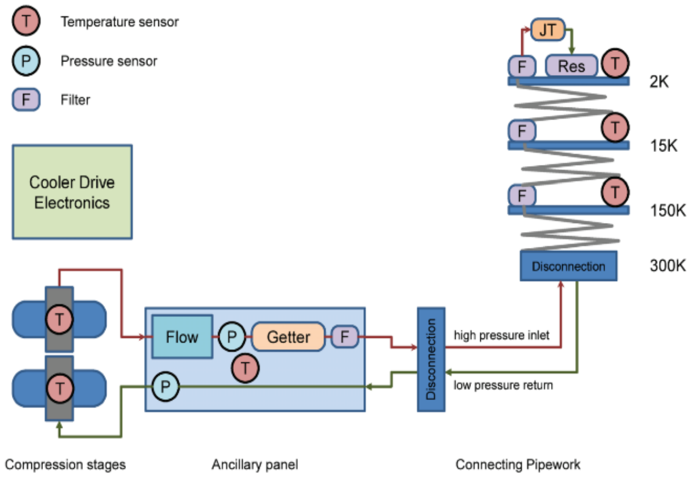


Rando, N. (2008)

ESA helped fund the development of a 4K (kelvin)[3] Joule-Thomson cryocooler for its PLANCK and HERSCHEL missions, based on the Oxford Stirling cooler technology. Now ESA is looking to build on these technology developments to equip its next generation of science missions (notably ARIEL's Ariel InfraRed Spectrometer (AIRS) and ATHENA's X-ray Integral Field Unit instrument (X-IFU)) with improved cryocoolers, meeting their stringent requirements. On top of needing to achieve the appropriate temperature operating ranges (30K for ARIEL and 2K for ATHENA), the Joule-Thomson cryocoolers must fulfil the overall mission requirements and thus need to be light, compact, vibration-free, limited in resource use, and long-lasting. Therefore, the CTP-funded activities have been focused on developing solutions with no moving parts and relatively simple components, so that they can be reduced in size, meet the mission requirements, and be produced with additive manufacturing technologies.

---

[1] There are two main cryocooler categories – recuperative cycles and regenerative cycles. Recuperative cycles move the working fluid around a loop in one direction at fixed high and low pressures. The Joule-Thomson cryocooler relies on recuperative cycles, with the cooling effect achieved by isenthalpic expansion of the cooling gas in an orifice. Brayton and Claude cryocoolers also use recuperative cycles. Regenerative cycles use oscillating flow and pressure with appropriate phase angles between the flow and the pressure. The Stirling cryocooler uses that principle, alternately compressing and expanding a fixed quantity of nearly perfect gas in a closed cycle. Pulse Tube and Gifford-McMahon cryocoolers use regenerative cycles.
[2] NIST (n.d.). *Cryogenic Technology Resources*, available at: https://trc.nist.gov/cryogenics/cryocoolers.html; Shapiro, et al. (2017), *Ceramic 3D printed Joule Thomson mini cryocooler intended for HOT IR detectors*, Proceedings of the SPIE (10180)
[3] Kelvin (K) is the SI base unit of temperature. The Kelvin scale is an absolute thermodynamic temperature scale, using absolute zero as its null point. For reference 4K= -269.15°C.



2K JT cryocooler (ATHENA) Crook, et al. (2016)

These technology developments are being undertaken by UK organisations: Science and Technology Facilities Council-Rutherford Appleton Laboratory (STFC-RAL), a UK-based scientific research and development institute that is part of UK Research and Innovation (UKRI), and Honeywell, a global aerospace leader. Both possess considerable experience in supplying cryocoolers, including for space, with STFC-RAL leading on the design and Honeywell Hymatic driving manufacturing activities.

The STFC-RAL-Honeywell partnership is particularly competitive, thanks to their **technical expertise** and **global reputation**. STFC-RAL were notably the first to develop a long-life compressor for Stirling cryocoolers, equipping them with significant expertise in their field. STFC-RAL's coolers have been licensed to industry stakeholders in the US and UK (to its partner Honeywell), and have underpinned various high-profile science, EO, climate change and meteorological missions.

The 30K Joule-Thomson cryocooler for ARIEL, significant for being one of the first neon-fuelled JT-coolers designed for use in space, is nearing completion of technological demonstration. For ARIEL, the development of a Neon 30K Joule-Thomson cryocooler is nearing completion. For ATHENA, STFC-RAL and Honeywell are developing a 4K Joule-Thomson cryocooler, with technological readiness expected to be demonstrated within the next year and delivery anticipated within 3 to 4 years; STFC-RAL is also developing a 2K Helium-3 Joule-Thomson cryocooler, with the potential that it might be used on board the ATHENA mission.

… with potential for significant socio-economic benefits

Whilst the 4K JT-cooler, 2K JT-cooler and the 30K cooler are all still undergoing developments, some initial socio-economic benefits have been identified, with the potential of further impacts to come through their successful use for space science missions and for other fields of application – for STFC-RAL, Honeywell, the UK industry, and the broader European landscape.

Developing key expertise and knowledge for the UK landscape

Development of a family of Joule-Thomson cryocoolers

STFC-RAL has been at the forefront of state-of-the-art cryocooler development, with involvement in a wide range of high-profile scientific and operational missions. It has also positioned itself as maintaining a speciality in the development of Joule-Thomson (JT) coolers, which are beginning to be utilised more in certain space science missions which require a **varied, bespoke cryogenic approach** and therefore benefit from the flexibility of solutions from the JT-cooler design.

Thanks to ESA's support and demand for complex cryogenic chains that can reach lower temperatures, which for some missions are best addressed with JT-coolers at their core, STFC-RAL is now developing a suite of JT-coolers across a spectrum of lower temperatures. This includes[4]:

- 4K JT-cooler – providing cooling at temperatures around 4K (-269.15°C) and targeting science missions in space exploration and cosmology.
- 2K JT-cooler- providing cooling at temperatures as low as 1.7K (-271.45°C) and aiming to provide pre-cooling for the lowest temperature stages as part of sub-Kelvin cryogenic chain for large science missions in space exploration and cosmology.
- 30K JT-cooler – providing cooling temperatures at 30K (-243.15°C) and targeting missions for space exploration and Earth observation.

By developing this family of JT-coolers, STFC-RAL is able to be versatile in its solutions offering, as well as maintain its competitive leading knowledge and expertise in this type of cryocooler.

Additional development and expertise for cryocooler market

The cryocooler market was estimated to be worth **~€2.15 billion** (USD 2.3 billion) overall in 2020, with a projection to reach **~€2.9 billion** (USD 3.1 billion) by 2025 at a Compound Annual Growth Rate (CAGR) of 6%.[5]

Key driving factors for the cryocooler market globally include the rising adoption of cryocoolers in the semiconductor industry, superconducting magnets, and power systems, along with an increased use of the technology within the healthcare sector.

More significantly, an increasing demand for cryocoolers in space applications and the development of cryocoolers for microsatellite applications have also been identified as key factors driving its growth, with the recognition that cryocoolers are used in association with sensitive electronics and sensors for space payloads, requiring **high reliability** and **power efficiency**, **low vibration**, and the ability to survive long-term exposure to radiation. Opportunities for cryocooler manufacturers include implementing increased efficiency in cryocoolers for detector sensitivity and signal/noise ratio, as well as addressing the need for scaled-down cryocoolers for microsatellites.[6]

Through the development of complex 4K and 2K JT-cryocoolers, alongside its other cryocooler projects, STFC-RAL and Honeywell are well-positioned to help address some of these growing demands from the cryocooler market, through technology, expertise and licensing. This CTP work is particularly helpful to Honeywell for increasing its manufacturing footprint in Europe, an expanding market within which it seeks to develop further.

Strengthening the UK supply chain

Thanks to its leading position in cryocooler technology, especially with Joule-Thomson cryocoolers and certain Stirling coolers, STFC-RAL and Honeywell have built partnerships within the broader industry that have helped the UK become a key actor in the wider **cryocooler supply chain**.

The main element of this leadership sits with the compressor residing in the cryocooler, which is the same compressor for both JT-coolers and Stirling coolers, thus answering a variety of needs. STFC-RAL is the developer of these compressors, and provides licences to industry to utilise the design, including partner companies in Europe (i.e. Honeywell) and the United States. Therefore,

[4] STFC, 2020. *Joule Thomson Cycle Cryocoolers for Lower Temperatures*. Available at: https://www.technologysi.stfc.ac.uk/Pages/ASD_CRY_Cryocoolers_JouleThomsonCycle.aspx#
[5] MarketandMarkets, 2020. *Cryocooler Market with COVID-19 Impact and Analysis – Global Forecast to 2025.* Available at: https://www.marketsandmarkets.com/Market-Reports/cryocooler-market-247727537.html
[6] IBID

STFC-RAL (and Honeywell) are key suppliers within the supply chain for the UK but also on a broader global scale.

Supporting ongoing leadership in UK cryogenics sector

The state-of-the-art Joule-Thomson cryocoolers developed at STFC-RAL are playing a role in supporting **UK progression** and **leadership** within the wider cryogenic landscape.

Recognising that the UK has a strong cryogenic academic, science and business community, the Science and Technology Facilities Council (STFC) commissioned a "Cryogenics Impact Report" to determine the socio-economic impacts that its cryogenics cluster provides to the UK landscape.

The report projected that the direct impact of cryogenics at a UK-wide level could shift from around £170 million GVA (Gross Value Added) in 2015, to **between £1.6 and £3.3 billion by 2024** (~€1.86 to €3.85 billion), depending on the growth of the UK economy and sectors of high importance to cryogenics.[7] Furthermore, it outlined how STFC's engagement in cryogenics-related work brought wider benefits to society, including[8]:

- *Investing in national skills capabilities* – with direct impacts such as building leading capabilities in cryogenics through growing research, technical and business skills, as well as transferrable skills, such as how space-related technologies (i.e. cryocoolers at STFC-RAL and Honeywell) can be utilised in the aerospace and defence sectors.
- *Fostering collaborations between research and industry including SMEs* – through STFC and the British Cryogenics Cluster, there is a wide range of support through testing facilities, business incubation space, and coordination and networking events such as the Cryogenics Cluster Day hosted at STFC-RAL, bringing together industry and scientists.
- *Championing local and regional economic development* - cryogenics infrastructure has built up around STFC facilities, including STFC-RAL, with a variety of actors ranging from global corporations to niche expertise in industry and science. The combination of these stakeholders and infrastructure together provide a foundation for further business expansion and investment.
- *Securing societal well-being and improving the public's understanding of science* – a key example of this being STFC-RAL's cryocooler development for the Planck explorer mission, providing insight into complex science questions about the universe.

It is important to note that the Joule-Thomson cryocooler development at STFC-RAL is a small part of a much wider cryogenics ecosystem within the UK, but it still plays a role in growing **expert knowledge** at STFC-RAL and Honeywell and on cryocoolers in general, in delivering **socio-economic impacts** for the UK, and in supporting the country's **leadership** in the cryogenics sector.

Offering a solution for operating extremely sensitive scientific instruments

Providing a flexible, long-lasting solution

Thanks to its technological advantages of being a flexible, long-lasting solution, the JT-cryocooler supports the use of **highly-sensitive scientific detectors** for missions.

[7] Warwick Economics and Development, 2015. *Cryogenics Impact Report.*
[8] IBID

Whilst there are some technological limitations of Joule-Thomson coolers – for example, having a lower efficiency than Stirling coolers at higher temperatures – this becomes less and less important as the temperature requirements lower. Anything below 10K is not as easily achievable with the Stirling type of coolers, while JT-coolers have one of the most efficient cooling cycles at very low temperatures such as 4K-2K.

One of the largest technological benefits of JT-coolers however is that the extended architecture of the cooler is far more **flexible** than other types, making it simpler in terms of integration of the cooler into the instruments and spacecraft. Most coolers have 'noisy' compressors and vibrations; the Stirling cooler type, for example, would have to have the pumps next to the detectors of the payload, leading to the 'loudest' equipment sitting next to the most sensitive equipment. For the JT-cryocooler meanwhile, the compressors, ancillary panel and drive electronics ('warm units') can be located away from the heat exchangers ('cold units'), **minimising the risk of mechanical** and **electrical disturbances** from the warm units towards the sensitive instrument detectors.[9]

ATHENA is a mission where this makes a significant impact – its JT-cryocooler requires 20 compressors, and the cryocooler must sit right next to its detector. Hence having the 'warm unit' separated away from the detector is key.

Another technological benefit of the JT-cryocooler is that its heat exchangers are easily manipulated, and so, despite usually being around 6-8 m in total length, they can be formed into a **compact configuration**.[10]

Key component of the cryochain

There is a trend within the space science domain to seek the answers to more and more complex scientific questions, pushing for cutting-edge space science missions to explore topics such as the origins of the universe, the fundamental physical laws of the universe, how the solar system works, and the conditions for planet formation.

The development of these advanced space science missions has introduced the need for high-performance detectors that operate at less than 0.5K (-272.65°C), thereby driving a need for sub-Kelvin cryogenics for space applications[11]. The solution to this challenge has been achieved by the creation of **cryochains**, employing cooling technologies of **ever-decreasing temperatures**. A successfully-deployed example of a mission using this technique is the Planck spacecraft, which achieved its required cooling through a cryochain consisting of: a passive cooling chain of v-groove radiators, and a three stage active cooling chain of a 18K sorption cooler, a 4K JT-cooler, and, finally, a dilution refrigerator.[12]

As can be seen by this example, the 4K JT-cooler – developed by STFC-RAL for Planck – played a core role within the cryochain, and will continue to do so for future missions. The JT-cooler specifically is an important technology, since at very low temperatures it has one of the most efficient cooling cycles (i.e. at 4K, 2K), and so fulfils a **specific role** within the temperature range.

Supporting new terrestrial applications

Beyond the importance of the JT-cooler within the space domain, there are also potential terrestrial uses for the technology, including in the quantum technologies domain.

The National Quantum Computing Centre (NQCC) facility, currently being built with the aim to be completed by the end of 2022, will sit within STFC-RAL at the Harwell Campus. Its goal is to

[9] Crook, M., et al., 2021. *Performance Testing of a 2K Joule-Thomson Closed-Cycle Cryocooler*. International Cryocooler Conference Inc., Boulder, CO, 2021.
[10] IBID
[11] i.e. temperatures approaching 0K (-273.15°C)
[12] Crook, M., et al., 2021. *Performance Testing of a 2K Joule-Thomson Closed-Cycle Cryocooler*. International Cryocooler Conference Inc., Boulder, CO, 2021.

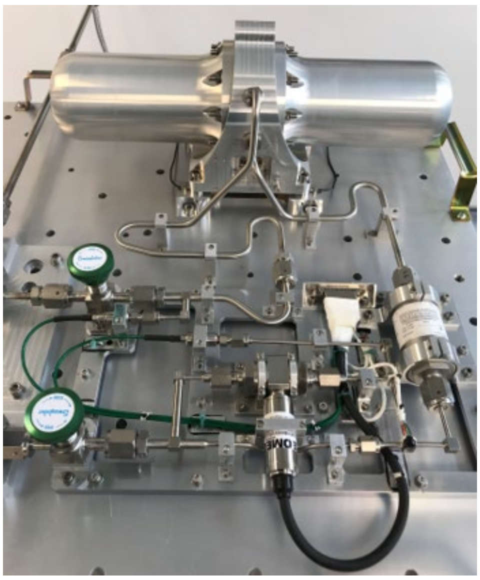
accelerate growth in Quantum Technology within the UK, working together with institutions such as STFC-RAL Quantum Space Lab and the STFC Cryogenics Lab. In general, STFC-RAL is involved in quantum technologies through the Quantum Communications Hub, as well as its Quantum Space Laboratory, focused on supporting academics and industry to prepare quantum technologies for use in space. Quantum technology is currently a key area of focus within the UK, being driven forwards by the UK National Quantum Technologies Programme (NQTP), which seeks to secure the UK's leading position in the domain, as well as stimulate market growth and develop a strong ecosystem.

Therefore, it is both a relevant area of interest for technological advancement, as well as being an opportunity for applying the use of JT-coolers to a growing domain. STFC-RAL is exploring the use of its 4K JT-cooler for applications such as **quantum imaging**, which explores the ability to produce highly efficient imaging in extreme spectral ranges, and **single photon detectors**, which are extremely sensitive devices capable of registering photons, providing essential technical support for optics quantum information applications. As outlined above, JT-coolers can provide the cooling system without a risk of disruption from vibrations and noise, notable when compared to other types of cryocoolers.

Honeywell is also in the process of partnering with a quantum-specialised UK software company to reuse the 4K J-T cryocooler developed for ATHENA for application in a **quantum key distribution (QKD) system**, which is a secure communication method for exchanging encryption keys between relevant parties. The QKD system would operate in the UK and would thus require specific wavelengths to penetrate cloud covers to reliably operate data transfers through satellites. In this case, the 4K J-T cooler would not be required to cool a sensor, but to cool the data transfer system.

Quantum computers in general require sub-Kelvin temperatures, indicating potential further uses for cryocoolers, as well as future possibilities in areas such cryogenically-cooled superconducting wind turbine generators, and superconducting power grids.

Space-related developments are particularly useful, because they answer the most stringent requirements for cooling solutions. This means that STFC-RAL, Honeywell and their products, can go above and beyond in answering terrestrial needs, which will be less demanding in terms of size, mass, and reliability (albeit still critical factors).



ARIEL 30K Cryocooler - STFC-RAL

STFC-RAL is also exploring the use of the 30K JT-cooler (developed for ARIEL) in further Earth Observation missions in space. Additionally, they are looking into terrestrial applications in applied superconductivity using MgB_2 (magnesium diboride), where ARIEL-type cryocoolers would cool **medical systems** (e.g. for magnetically targeted drug delivery, magnetic cell separation, and controlled local heating for the ablation of tumours)[13].

The compact and lightweight cooling offered by space coolers, like those examined in this case study, can benefit applications of **bulk superconductors** more generally. Beyond the medical applications outlined above, space coolers could benefit portable systems for bulk superconductivity, ultra-light superconducting rotating machines for next-generation transport and power applications, and magnetic shielding applications for electric machines, equipment and other high-field devices.[14]

[13] Hills, M. et al. 2018. *A Compact High Field Magnet System for Medical Applications.*
[14] Durrell, JH. Et al. 2018. *Bulk superconductors: a roadmap to Applications.*

Ensuring access to critical, mission-enabling technology for European actors

Enabling technology for space science missions

STFC-RAL's JT cryocooler development has and will play a **core enabling role** for space science missions, with past successes such as the Planck mission, and future missions such as ARIEL and ATHENA.

Planck was Europe's first mission dedicated to studying the Cosmic Microwave Background (CMB), launched in 2009 and ceasing operations in 2013. Its objective was to measure the fluctuations of the CMB with an accuracy set only by fundamental astrophysical limits, in order to chart detailed maps of the CMB. It sought to answer questions regarding the large-scale properties of the universe with high precision, test theories of inflation of the universe, and study the origin of structures that can be seen in the universe today. Its instrument detectors were so sensitive that even a temperature variation of a few millionths of a degree were distinguishable – an **unrivalled sensitivity** that was enabled in part by the 4K STFC-RAL-developed JT cryocooler.[15]

ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is a medium class (M-class) mission selected for ESA's Cosmic Vision programme, and due to be launched in 2029. Its objective is to explore questions regarding exoplanets, including what they are made of, how they are formed, and how they evolve, through surveying a diverse sample of 1000 exoplanets in visible and infrared wavelengths.[16] STFC-RAL will be providing a 30K JT-cooler for the mission, utilising similar architecture to the Planck mission in terms of cooler accommodation and integration. This 30K JT-cooler will provide the Active Cooler System (ACS) of the cold Payload Module (PLM), which is necessary for enabling the operation of the Ariel InfraRed Spectrometer (AIRS).[17]

One of the more complex science missions under development is ESA's L-class ATHENA (Advanced Telescope for High-Energy Astrophysics), which will be an X-ray telescope designed for ESA's Cosmic Vision theme of 'The Hot and Energetic Universe', to be launched in 2035. Its primary goals are to address two key astrophysical questions – how ordinary matter assembles into the large-scale structures seen in the universe today, and how black holes grow and shape the universe.[18] ATHENA's X-ray Integral Field Unit (X-IFU) spectrometer instrument is a key payload that will require a complex cryochain, within which a JT-cooler will play a critical role. Therefore, STFC-RAL is developing a 4K JT-cooler as part of ATHENA's cryogenic chain, as well as a 2K JT-cooler for potential use in the mission also, building on their knowledge of previous JT-coolers such as the cooler from the Planck mission. These JT-coolers will play a **core enabling role**, ensuring the complex instruments on board will be able to operate properly. Notably, this solution will be far more challenging than what has come before: the mission needs 20 compressors, as opposed to only 1 for ARIEL.

Supports European non-dependence

A key objective of the European Commission, the European Space Agency and the European Defence Agency is to ensure European "**non-dependence**" for critical space technologies – defined by the possibility of Europe to have "free, unrestricted access to any required space

[15] European Space Agency, 2022. *Planck Science objectives*. Available at: https://www.esa.int/Science_Exploration/Space_Science/Planck/Science_objectives
[16] European Space Agency, 2022. *Ariel Summary.* Available at: https://sci.esa.int/web/ariel/-/59798-summary
[17] Hills, M. et al., 2021. *A Neon JT Cooler for Ariel.* Available at: https://cryocooler.org/resources/Documents/C21/423.pdf
[18] European Space Agency, 2022. ATHENA mission summary. Available at: https://sci.esa.int/web/athena/-/59896-mission-summary

technology".[19] This is in comparison to "independence" (that all needed space technologies must be developed in Europe).

As outlined above, certain flagship space science missions could not be launched without the use of JT-coolers to enable the use of complex, sensitive instruments, as key science questions push the boundaries of technology further and further. Therefore, 4K and 2K JT-cryocoolers are considered core technology solutions, **critical for the development of missions**.

Thanks to STFC-RAL's ongoing development in this domain, especially with the use of the 4K JT-cooler on Planck and the introduction of the 4K and 2K JT-coolers for ATHENA, they are providing a European-developed solution that ensures there is no dependence from Europe to purchase/import these coolers from elsewhere around the world, and hence no restrictions in place for accessing this critical space technology. Honeywell's manufacturing of these cooling solutions is also critical in ensuring that Europe is able to supply and use them with no dependence on third-party countries.

Increased European competitiveness

The development of high quality, technologically advanced Joule-Thomson cryocoolers such as the 2K JT-cooler has not only allowed Europe to establish its non-dependence in building this important solution, but has also increased its **competitiveness** on a global level.

The STFC-RAL-designed JT-coolers are competitive in terms of **capability** and **compactness** in comparison to other products on the market, such as those being produced in the United States. Furthermore, they are **long-life** cryocoolers, which is crucial for space missions where the lifespan of the cryocooler should not be the limiting factor in the length of expensive, complex science missions; with the STFC-RAL designs, the JT-cooler will last as long as necessary for the mission and its lifespan doesn't have to be taken into consideration. This is in contrast to almost all other competitors in the global market, which degrade over time and hence have a lifespan of only 2-4 years, far from the ~10 year lifespan of missions like ATHENA.

Finally, as the technology was developed and produced in Europe, it is free of export restrictions that could otherwise limit its use by other countries.

Would these benefits have been realised without ESA?

ESA

The benefits outlined in the above sections would not have occurred, or would have been significantly limited, without CTP funding, above all due to the fact that all three key JT-coolers were designed for the purpose of addressing ESA demands for specific missions.

Notably, the ARIEL and ATHENA missions would be difficult, if not impossible, to implement without the CTP-funded solutions developed by STFC-RAL and manufactured by Honeywell. Beyond enabling boundaries-pushing science missions, successive ESA technology development contracts going back to PLANCK's 4K J-T cryocooler have enabled STFC-RAL to gain cutting-edge expertise and global leadership in space cryogenics, which is source of a plethora of benefits, as outlined above. Overall, ESA's support has been critical in catalysing UK and European excellence in the field.

> *"CTP support has been instrumental in the development of these cryogenic solutions"*
> - *Martin Linder, ESA*

[19] European Commission, 2021. *Space Technologies for European Non-Dependence and Competitiveness.* Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/guidance/guidance-document_horizon-cl4-2021-space-01-81_horizon-cl4-2022-space-01-81_en.pdf

… plus further development and benefits to come

STFC-RAL's developments for the ARIEL mission are reaching the final technical and demonstration stages, as the mission is due to be launched in 2029. For ATHENA, development activities are picking up and significantly accelerating, but considerable challenges are yet to be overcome simply due to the notable complexity of the mission. STFC-RAL and Honeywell will be focused on these efforts for the coming years, as the mission is set to be launched in 2035. This is likely to further the wide-ranging benefits outlined in this report. Additionally, both partners anticipate they will explore how to use the technology, techniques and processes developed through these CTP-funded projects for terrestrial applications, as outlined in earlier sections.