CRYOCLOCK (FORMERLY SAPPHIRE CLOCK) AN ON PROGRAM CASE STUDY

BOX 1 CRYOCLOCK (SAPPHIRE) CASE STUDY - EXECUTIVE SUMMARY

Key findings

The CryoClock project has produced the following outputs:

- Successful demonstrated the Sapphire Clock technology
- Built and sold a prototype clock for use in the Nanotech Lab
- Provided other clocks to overseas labs
- Collaborated with the Department of Defence to test the use of the Sapphire Clock in the JORN facilities.
- Won the Eureka Price for Outstanding Science in Safeguarding Australia (2018)

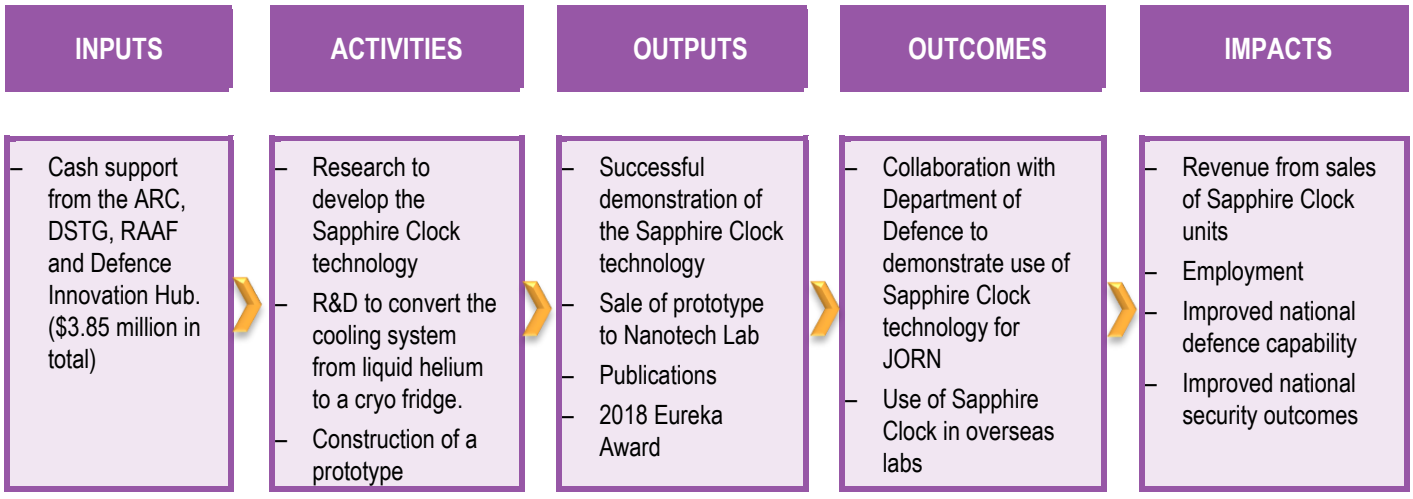
If the technology is successfully used with JORN then there are likely to be sales of a least twenty units, and some 20 jobs will be created. Export sales to allies are also possible.

Role played by CSIRO ON

Participation in CSIRO ON enabled the project team to investigate the commercial prospects for Sapphire Clock such as its developmental priorities, viability and customer needs. It gave the team the confidence to pursue commercialisation and realise the market potential of the technology approximately 12 months sooner than would otherwise have been the case. The team chose the CSIRO ON program over others because it is a trusted party that is backed by scientific expertise and is familiar with universities and research agendas.

This case study uses the evaluation framework outlined in the CSIRO Impact Evaluation Guide. The results of applying that framework to the CryoClock case study are summarised in **Figure 1.1**.

FIGURE 1.1 SAPPHIRE CLOCK CASE STUDY – IMPACT FRAMEWORK DIAGRAM



SOURCE: ACIL ALLEN

1.1 Purpose and audience for case study

This case study describes the economic, environmental and social benefits arising from the Sapphire Clock project.

This evaluation is being undertaken to assess the positive impacts arising from the Sapphire Clock project's participation in the CSIRO's ON. This case study can be read as a standalone document or aggregated with other case studies to substantiate the impact and value of the CSIRO ON activities as a whole, relative to the funds invested in these activities.

The information in this case study is provided for accountability, communication and continual improvement purposes. Audiences for this report may include Members of Parliament, Government Departments, ON, CSIRO and the general public.

1.1.1 CSIRO ON

CSIRO ON was established in 2015 by CSIRO to help accelerate the impact of science research into market. The initiative was expanded through funding from NISA to service more broadly Australia's publicly funded researchers and their industry partners. The aim of the initiative is to more quickly translate great science and technology research into positive impact to help address some of the economic, environmental and social challenges facing the Australian and global community.

There are a number of elements to the program, including two facilitated programs, ON Prime and ON Accelerate. These two elements are designed to complement each other.

ON Prime is an open and collaborative program for existing science projects as well as new technologies and projects that are still in development. ON Prime helps research teams to ensure that they are working on the right problem, it provides frameworks to create and test assumptions about their idea and provide recommendations towards next steps. ON Prime can be considered as an entry level program, in effect it can be seen as a precursor to participation in the ON Accelerate program.

ON Accelerate is designed for teams that have made significant progress with their idea and their target market(s). This may be in the form of contracts for paid or unpaid trials, or at the most advanced stage, recurring sales with both new and existing customers. This implies that teams will have a working prototype of their product or service and have secured any appropriate intellectual property rights. It is expected that teams applying for ON Accelerate would have conducted significant engagement with their potential customers and be able to demonstrate what they learned throughout, including what the total addressable market is and what competition exists.

For ON Accelerate, shortlisted applicants are invited to participate in a two-day Selection Bootcamp event where teams will be provided with training and coaching simulating the accelerator experience. At the conclusion of the selection bootcamp, the teams will pitch to a panel of external judges for a spot in the Accelerator. Projects that are at Investment Readiness Level (IRL) Stage 3 can apply directly for ON Accelerate without going through Prime or Bootcamp.

Following a team's passage through the ON Prime or ON Accelerate program they are eligible to apply for ON Runway support. That funding is designed to help teams to further progress their project. The support provided can be spent on a range of services, for example, regulatory certification, marketing, bookkeeping or investor agreements.

1.2 Background

The cryogenic Sapphire Oscillator — otherwise known as the Sapphire Clock —is the culmination of two-decades of research and development. It is an ultra-low phase-noise frequency oscillator that can be used for extremely stable generation of radio frequency and microwave signals. It uses a Whispering Gallery Mode of a cryogenically cooled sapphire crystal to form an ultra-stable oscillator generating a frequency of approximately 10.6GHz. A closed refrigeration system results in a low maintenance cycle of 20,000 hrs.[1]

The Sapphire Clock has been developed by the University of Adelaide's Institute for Photonics and Advanced Sensing (IPAS) and start-up company CryoClock Pty Ltd. The Clock's componentry was first developed at the University of Western Australia in the mid-1990s-2000s by doctoral students Andre Luiten and John Hartnett who were interested in improving the precision of time and frequency measurements. The intention was to use the technology as part of the gravity wave detector experiment then being conducted at UWA.

[1] Cyrogenic Sapphire Oscillator System Specification, CryoClock Ltd Pty. Viewed at https://www.cryoclock.com/ (010219)

The breakthrough made by their research was determining how to use the unique property of sapphire crystals, which when cooled to extremely low temperatures are able to store microwave energy for an extended period.[2] When microwave-radiation is injected into the sapphire crystal it propagates around the circumference of the crystal, making it ring like a bell. The technology makes it possible to use these regular vibrations to measure the passage of time.

Precision time and frequency is critical in many sensing, communication and computational tasks. It is particularly important in radar technology, very long baseline radio astronomy and quantum computing.[3]

1.2.1 The science behind the Sapphire Clock project

The Cryogenic Sapphire Oscillator has a 5cm cylinder-shaped sapphire crystal that is cooled to about -267 °C, about 5 or 6 degrees above absolute zero. At this temperature, the rate of microwave energy loss in the sapphire crystal is the lowest of any substance on Earth. Microwave radiation is injected into the sapphire crystal and propagates around the circumference of the crystal (just inside the surface). The way the microwave radiation moves around the crystal is like a phenomenon called a Whispering Gallery. Lord Rayleigh first discovered this concept in 1878 when he could hear someone whispering far away on the other side of the church dome at St Paul's Cathedral.[4]

The Sapphire Clock works on a fundamentally different principal from the quartz oscillators that are typically used in radar installations. Quartz oscillators use acoustic radio-frequency oscillators whereas the sapphire device operates by trapping an electromagnetic signal that has a frequency 1000 times higher than a quartz oscillator, resulting in better signal accuracy.[5]

The Sapphire Clock has 10-1000 times higher stability and lower phase noise than any other competing technology. Its precision enables increased spatial resolution for phased-array radar and GPS navigation, and higher capacity for beam-forming 5G communication.[6] Stable oscillators are required for next generation MIMO (multiple input, multiple output) and distributed radar systems for defence, autonomous vehicles, improve spectral efficiency for higher bandwidth utilisation for 5G wireless and beyond, as well as quantum computing fabrication.

A second important element to the project was the design and construction of a cryogenic fridge to cool the sapphire crystal. This development enabled the technology to become much more portable and opened the door to commercialising the technology. Previously the crystal was cooled with liquid helium.

1.3 Impact Pathway

1.3.1 Project Inputs

The total cost of the project was about $3.85 million since 2015 in cash (see **Table 1.1**). These funds predominantly came from the defence sector. According to CSIRO, the overhead costs of the ON program that have been apportioned to the Sapphire Clock project total $22,895.

TABLE 1.1 SUPPORT FOR THE PROJECT

Contributor / type of support	2015 ($ m)	2016 ($ m)	2017 ($ m)	2018 ($ m)
Cash				
Australian Research Council (ARC)*	$0.2	$0.2		
Defence Science and Technology Group (DSTG)	$0.15	$0.25		
RAAF/DSTG combined		$0.5	$0.5	$0.5
Defence Innovation Hub (Commonwealth Government)			$1	$1
Total	**$0.35**	**$0.5M**	**$1.5M**	**$1.5 M**

*The ARC provided $200,000 per year for Prof John Hartnett (ARC Discovery Outstanding Researcher Award).

[2] Application for the Eureka Prize 2018

[3] O Connor, M et al Cryogenic Sapphire Oscillator Enhancement Improves Accuracy, Cold Facts 33, 1 (February 2017)

[4] The Sapphire Clock, Institute for Photonics and Advanced Sensing, Adelaide University. Viewed at https://www.adelaide.edu.au/ipas/research/nls/pmg-research/SapphireClock/ (31/01/19)

[5] Application for the Eureka Prize 2018.

[6] Sapphire Clock: delivering precision timing for next-gen electronics infrastructure, ON Prime Application.

1.3.2 Project activities

The Sapphire Clock is the culmination of two-decades of research and development. The work began in the mid-1990s with research to develop a superior oscillator using a super cooled sapphire crystal to improve the precision of time and frequency measurements. The technology was intended for use as part of the gravity wave detector experiment at UWA. Initially liquid helium was used to cool the sapphire clock.

In 2011-12 the researchers moved to South Australia and set up the Cryogenic Sapphire Oscillator research lab. Four other researchers then joined the group. Research was then done to replace the liquid helium by a cryogenic fridge. This opened the door to commercialisation of the sapphire clock.

Role of the ON program

Through the ON program, the project team realised that the original business plan for the Sapphire Clock was overly complex, the value proposition and customers were too broadly defined, and the revenue channels undeveloped.[7] The research team's participation in the ON program facilitated a market discovery process that identified an appropriate market focus, both in the short-term and the long-term, namely that support for military radar was the most profitable target market.

The need to report back to the other participants in the ON Program in relation to the number of approaches that had been made to potential customers for the Sapphire Clock created a level of accountability that helped to keep the project team on track.

1.3.3 Project outputs

Publications

The research team identified the following as being among their most significant publications:

- W. A. Al-Ashwal, A. Hilton, A. N. Luiten, J. G. Hartnett, Low Phase Noise Frequency Synthesis for Ultra-Stable X-Band Oscillators, *IEEE Microwave and Wireless Components Letters* 27, 392-394 (2017).
- J. G. Hartnett, M. E. Tobar, E. N. Ivanov, A. N. Luiten, Optimum design of a high-Q room temperature whispering-gallery-mode X-band sapphire resonator. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 60, 1041-1047 (2013).
- S. Chang, A. G. Mann, A. N. Luiten, Improved cryogenic sapphire oscillator with exceptionally high frequency stability. *Electronics Letters* 36, 480-481 (2000).
- J.G. Hartnett and A.N. Luiten, Colloquium: Comparison of astrophysical and terrestrial frequency standards, *Rev. Mod. Phys*. 83, 1-9 (2011).

Awards

The Sapphire Clock won the Eureka Prize for Outstanding Science in Safeguarding Australia in 2018. The citation for the award stated:

By combining two decades of pioneering research with cutting-edge engineering, the Sapphire Clock Team's technology offers the potential for a step change in the performance of the Jindalee Over-The-Horizon Radar Network, a vital Australian defence asset. The Sapphire Clock offers a thousandfold improvement in timing precision, helping Australian defence agencies identify threats to the nation.

Innovation / commercialisation

A significant commercialisation activity is the work with DST Group, the Royal Australian Air Force (RAAF) and Capability, Acquisition and Sustainment Group at the Department of Defence for the provision and construction of two sapphire clocks.[8] The intention is to use the Sapphire Clock in the Jindalee Over-The-Horizon Radar Network (JORN). The JORN radars are important to Australia's defence capability. Australia's ability to support this independently (to not rely on other nations) is important to our national security. The technology is expected to contribute to improving JORN's resolution and aiding detection of smaller vessels.

In 2016 the team's principal researchers established a company (CryoClock Pty Ltd) that has taken an order to supply a beta version unit for a non-military application in quantum computing. If the technology delivers the anticipated results it is expected to lead to further orders from the quantum computing research community.

The telecoms sector is a potential longer-term market. The device could be used in the 5G network to help reduce the "jitter" in machine to machine communications by sending signals from a central control point to individual telecoms towers.

[7] Sapphire Clock presentation during ON PRIME

[8] The Hon Christopher Pyne MP (Minister for Defence Industry) Letter of Support for the nomination of the Sapphire Clock for the Eureka Prize 201).

The Sapphire Clock researchers are protecting their Intellectual Property (IP) by ensuring that the design and tolerance of parts, circuit design and layout as well as the assembly process are trade secrets.

In addition to the Sapphire Clock, the team has developed two additional technologies: an ultra-low noise synthesis technology that can take clock signals and generate the frequencies that are needed by the radar and; signal dissemination technology over optical fibre which enables them to deliver the pure signals to numerous locations. These developments have been described as a 'revolutionary leap' in the performance of the invention.[9]

Role of ON program

The research team's participation in ON brought the researchers out of the labs and into a setting that required a business 'mindset' (i.e., thinking about product development, talking to customers about their needs and advancing their thinking around their business case). ON was successful in changing their mindset, and it gave them greater confidence to make the transition towards commercialisation.

1.3.4 Project Outcomes

The Defence Science and Technology Group (DSTG) engaged the Sapphire Clock project team to work on the Jindalee Over-the-Horizon Radar Network (JORN). JORN is a long-range radar that plays a key role in Australia's defence surveillance and disaster relief capabilities. For JORN's radar application the Clock delivers a signal that is more than 1000 times purer than its existing approach.[10] The Commonwealth is engaged in a process to acquire the Sapphire Clock technology to support JORN through its $1.2 billion Project Air 2025 Phase 6 upgrade.

When manufacturing of the device begins it is anticipated to generate 10-15 new jobs (end of 2019) and up to additional 20 jobs in the subsequent years.

Role of the ON program

Participation on the ON program was instrumental in advancing the research team's thinking around their business case and encouraged them to change their mindset and to make the transition towards commercialisation of the technology.

1.3.5 Adoption

The development of the Clock through the JORN project (the Clock is small part of the $1.5 billion project) is expected to see manufacturing start at the end of 2020. The Department of Defence will order at least 10 units to meet the needs of JORN. If the technology is successfully applied to JORN then there may be opportunities for export earnings from selling the technology to Australia's allies.

In addition to being installed in a quantum computing program, sapphire clocks have been installed in the Paris Observatory, in two Japanese national laboratories and the Korean national measurement laboratory.

Role of the ON program

The ON program helped the research team to determine the most appropriate market for their technology.

1.3.6 Impacts

The Sapphire Clock is described as central to Australia's sovereign industrial capabilities. It is an example of what the Australian Defence Industry Policy Statement[11] describes as a capability that must be developed or supported by Australian industry because overseas sources do not provide the required security or assurances.[12] Initial tests of the Sapphire Clock by the DSTG has shown substantial end-to-end system benefits which mean that Australia's key surveillance asset will gain a substantial benefit.

The revenue from this technology to date is over $600,000 from various projects.

There will also be revenue from the sale of units to the Department of Defence for use with JORN. As these units will be constructed to defence specifications it is likely that unit costs will be higher. ACIL Allen has assumed that the unit cost will be in the order of $1 million. Construction of the units is assumed to begin in 2020 and occur over 3 years.

[9] Application for the Eureka Prize 2018

[10] The Sapphire Clock, Institute for Photonics and Advanced Sensing, Adelaide University. Viewed at https://www.adelaide.edu.au/ipas/research/nls/pmg-research/SapphireClock/ (31/01/19)

[11] Department of Defence, Australian Defence Industry Policy Statement 2016.

[12] Application for the Eureka Prize 2018.

1.4 Clarifying the Impacts

1.4.1 Counterfactual

The research team estimated that their participation in the ON program had sped up their commercialisation process by approximately 12 months. Hence in the absence of the ON program ACIL Allen assumes that the sales of Sapphire Clocks to the Department of Defence would have been delayed until 2021.

1.4.2 Attribution

The net present value of the difference in revenue flows due to a one-year delay in sales is attributed to the ON program.

1.5 Evaluating the Impacts

1.5.1 Cost-Benefit Analysis

Costs

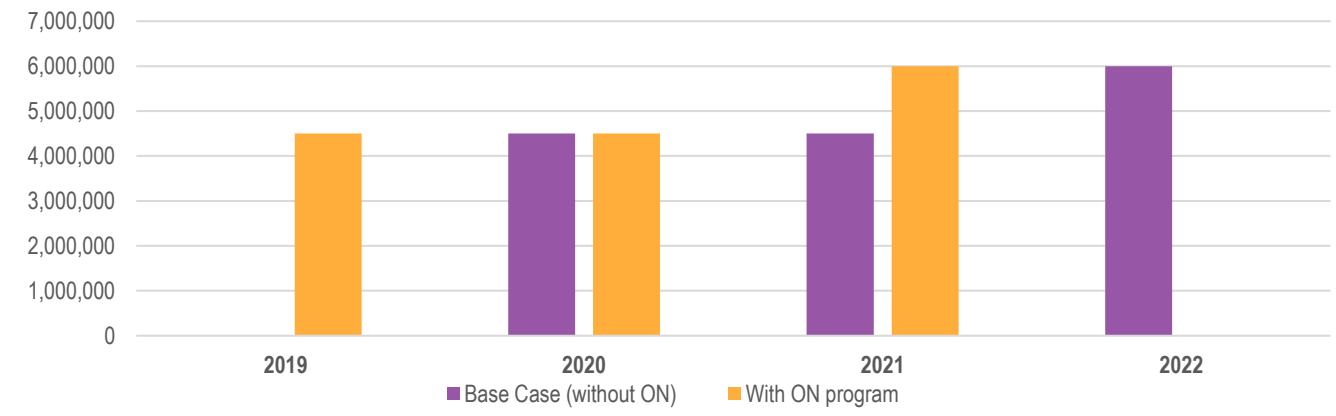
The costs to the Sapphire Clock team of participating in ON program activities are estimated to be $25,000. According to CSIRO, the overhead costs of the ON program that have been apportioned to the Sapphire Clock project total $22,895. Both sets of costs are assumed to be incurred in 2018.

Benefits

In the Base Case (that is, without the ON program), it is assumed that the sapphire clocks would be delivered to the Department of Defence for the JORN program one year later than in the case with the ON program (that is, 3 units in 2021, 3 units 2022 and 4 units in 2023 in the Base Case, compared with 3 units in 2020, 3 units in 2021 and 4 units in 2022 with the ON program). It is assumed that each clock for the JORN program is sold for $1 million, together with a $500,000 maintenance / support contract.

The value of sapphire clocks sold, including their associated maintenance contracts, between 2018 and 2023 under the Base Case and the with-ON program case is shown in **Figure 0.2**.

FIGURE 0.2 VALUE OF SAPPHIRE CLOCKS SOLD, INCLUDING MAINTENANCE CONTRACTS, WITH AND WITHOUT ON PROGRAM, 2018 TO 2023 ($)



SOURCE: ACIL ALLEN

It is assumed that most of the value added in the manufacture of the Sapphire Clock is retained in Australia, with only 20 per cent "leaking" out of the Australian economy (due, for example, to some foreign-sourced inputs).

Assessment of benefits against costs

The present value of ON-related costs is estimated to be $52,336 in 2019 dollars under a 7 per cent real discount rate. The present value of benefits from the accelerated commercialisation and production of the Sapphire Clock as a result of the ON program is estimated at $729,897 in 2019 dollars under a 7 per cent real discount rate.

The net benefit or net present value (NPV) of the ON program in relation to the Sapphire Clock is thus estimated at $677,561 in 2019 dollars under a 7 per cent discount rate. The benefit-cost ratio (BCR) is estimated at 13.95.

Sensitivity analysis

Sensitivity analysis has been undertaken to test the robustness of the cost-benefit analysis results to changes in key assumptions and parameter values.

In the central case of the cost-benefit analysis, it is assumed that the value of the maintenance/support contracts as a proportion of the sale price of the sapphire clocks to the Department of Defence is 50 per cent. If this proportion is 25 per cent, the BCR falls from 13.95 to 11.62. If the proportion is 75 per cent, the BCR rises to 16.27.

In the central case of the cost-benefit analysis, it is assumed that the "leakage" of value added in Sapphire Clock production from the Australian economy is 20 per cent. If this proportion is 10 per cent, the BCR rises from 13.95 to 15.69. If the proportion is 30 per cent, the BCR falls to 12.20.

A real discount rate of 7 per cent was used in the central case of the cost-benefit analysis. Under a 4 per cent discount rate, the BCR falls from 13.95 to 8.69. The BCR rises to 18.32 under a 10 per cent discount rate. This is because participation in the ON program brings forward the benefits from the sale of the sapphire clocks to the Department of Defence, so that the difference in benefits relative to the Base Case (after taking into account the leakage in value added from the Australian economy) is $3.6 million in 2019, $0 in 2020, $1.2 million in 2021 and -$4.8 million in 2022. A higher discount rate reduces the present value of the large negative benefits (that is, dis-benefits) in 2022.

1.5.2 ON program's role

The research team's participation in ON helped the researchers to think about product development, talk to customers about their needs, decide on the most appropriate technology for their technology and helped to advance their thinking around their business case. Participation in the ON program gave them the confidence needed to make a more rapid transition towards commercialisation.