Institution: EaStCHEM School of Chemistry		
Unit of Assessment: UoA 8: Chemistry		
Title of case study: New phase-change materials enable commercialisation of energy-efficient, sustainable and cost-effective domestic heat storage, resulting in robust company growth and a reduction in fuel poverty		
Period when the underpinning research was undertaken: 2010 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Colin Pulham	Professor of High-Pressure Chemistry	September 1992 – present
Period when the claimed impact occurred: 1 August 2013 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research by EaStCHEM Professor Colin Pulham has solved long-standing stability issues associated with phase-change materials (PCMs) based on salt hydrates, making possible the development of new formulations that efficiently store and reproducibly release heat on demand. With these new patented formulations at their core, UK-based *Sunamp Ltd* have brought to market the world's first commercially viable residential heat batteries.

Sunamp has created 52 jobs (headcount: 52; FTEs: 50), raised investment of GBP12,000,000, and generated total revenue of GBP10,000,000 between 1 August 2013 and 31 December 2020. From the early *SunampPV* model, deployed in large UK trials from 2015 (1,000 installed), the company has expanded to bring to market the *UniQ* model, sold worldwide since 2018 (5,000 sold to 12-2020, 20% internationally). Orders grew twelve-fold between 2019 and 2020; by 12-2020, *Sunamp* had an order book worth GBP50,000,000. In recognition of this robust growth, in 2020 the company signed the lease for a factory in South Korea, where an annual capacity of up to 60,000 units will meet initial demand from Asian markets.

For domestic heating, *Sunamp* heat batteries can be charged with energy from almost any source, provide high efficiency storage, and release heat on demand. They have saved homeowners money and reduced carbon emissions by minimising heat loss from storage and increasing use of locally generated renewable energy and cheap off-peak electricity. Recognising the potential of heat batteries to reduce costs for homeowners most in need, *Sunamp* has worked with UK housing associations to install heat batteries in 1,500 properties, lowering bills and increasing comfort for residents at risk of fuel poverty.

2. Underpinning research

The challenge: solving the stability issue of heat storage materials

Heat storage technology has a key role to play in increasing both energy efficiency and the use of renewables in the heating and cooling sector, which contributes almost 40% of global energy-related carbon emissions (*International Energy Agency* report, 2018). The core component of heat battery technology is a phase change material (PCM) that absorbs heat on melting and releases it on freezing. Salt hydrates are leading candidates for use as PCMs due to their high energy density, plentiful supply, low cost, safe use and sustainability. In particular, sodium acetate trihydrate (SAT), with a melting point of 58°C, provides heat release at an ideal temperature for domestic use. However, SAT suffered from two key issues that resulted in non-reproducible performance and poor long-term stability, thus preventing its practical use as a heat store. Firstly, incongruent melting of SAT led to irreversible phase segregation into undesirable anhydrous sodium acetate. All previous attempts to solve this problem relied on either (1) working with more dilute solutions of SAT, causing decreased energy densities and less welldefined freezing points, or (2) use of thickening agents that merely suspend the denser anhydrous SAT in solution. Secondly, SAT exhibits sub-cooling, whereby crystallisation does not occur until substantially below its freezing point. Whilst this can be overcome through the use of a nucleating agent based on disodium hydrogenphosphate (DSHP), it has previously been observed that this nucleating agent deactivates through an unknown mechanism if heated above 75-80°C.

Overcoming incongruent melting and sub-cooling to provide reliable and long-lasting PCM heat storage
UK-based SME *Sunamp Ltd* began developing heat battery technology in 2006 but found that the failure of SAT prevented progress. Seeking research input to tackle this problem, the company made contact with EaStCHEM Professor Colin Pulham, who brought expertise in crystallisation science **[R1, R2]**. Collaborative research led by Pulham for *Sunamp* (2010-2014) succeeded in overcoming incongruent melting by developing polymer-based additives that at low concentrations act as crystal-habit modifiers, suppressing the formation of the solid anhydrous sodium acetate. As a result, the new SAT-based material withstands repeated melting and freezing cycles without degradation, while maintaining both its energy density and the desired melting point of 58°C. *In situ* X-ray powder diffraction experiments at the *Diamond Light Source* were used to interrogate, in real time, the structural and chemical behaviour of these new SAT formulations during repeated temperature cycling, and confirmed complete inhibition of the precipitation of anhydrous sodium acetate over a wide range of conditions **[R3]**.

X-ray diffraction studies also identified, for the first time, that the active form of the nucleator is the dihydrate of DSHP and that thermal deactivation of this nucleator is caused by its dehydration into anhydrous DSHP, which does not act as a nucleator **[R3]**. These results identified the dehydration temperature of DSHP dihydrate and enabled *Sunamp* to configure its heat batteries to avoid deactivation.

This work resulted in a new formulation of PCM based on SAT that retains its high energy density and thermodynamic stability over multiple cycles (>40,000 shown in testing), with retention of a distinct and reproducible freezing/melting transition. Patent protection for the formulation was granted in 2014 **[R4]**. This PCM has set the international standard for cycling stability through the *RAL Quality Mark*, gaining the first and only *A Grade RAL Certification* for stability over 10,000 cycles.

Further work (2014-2015), supported by EPSRC Impact Acceleration Account funding, identified an alternative, cost-effective bulk source of the essential polymer component, to enable production of the SAT PCM formulation at a price compatible with large-scale commercialisation.

The developed research methodology has subsequently been used (2015 to present) to produce PCM formulations (and additional joint Pulham-*Sunamp* IP) based on other salt hydrates with different melting temperatures, including strontium bromide hexahydrate (88°C – for higher temperature radiator storage) **[R5]** and calcium nitrate tetrahydrate (43°C – with applications for coupling heat batteries to low temperature heat pumps, and heat packs for treatment of frostbite) **[R6]**. Investigation of potential isostructural relationships between nitrates of magnesium, calcium, and strontium resulted in the discovery and characterisation of a nucleator for formulations based on calcium nitrate tetrahydrate, enabling reproducible nucleation.

3. References to the research
The underpinning research was published as peer-reviewed outputs in well-regarded journals and has resulted in multiple granted patents. The PCM described in **[R4]** has set the international standard for cycling stability through the *RAL Quality Mark*.

R1. I.D.H. Oswald, A. Hamilton, C. Hall, W.G. Marshall, T.J. Prior and **C.R. Pulham**, "In-situ characterization of elusive salt hydrates - the crystal structures of the heptahydrate and octahydrate of sodium sulfate", *J. Am. Chem. Soc.*, **2008**, *130*, 17795-17800. DOI: 10.1021/ja805429m.

R2. I.D.H. Oswald, I. Chataigner, S. Elphick, F.P.A. Fabbiani, A.R. Lennie, J. Maddaluno, W.G. Marshall, T.J. Prior, **C.R. Pulham** and R.I. Smith, "Putting pressure on elusive polymorphs and solvates", *CrystEngComm,* **2009**, *11*, 359-366. DOI: 10.1039/B814471K.

R3. D.E. Oliver, A.J. Bissell, X. Liu, C.C. Tang and **C.R. Pulham**, "Crystallisation studies of sodium acetate trihydrate – suppression of incongruent melting and sub-cooling to produce a reliable, high-performance phase-change material", *CrystEngComm*, 2021 (e-pub **8 Dec 2020**), *23*, 700-706. DOI: 10.1039/D0CE01454K.

R4. A.J. Bissell, D. Oliver and **C.R. Pulham**, "Improved Phase Change Compositions", *Granted patent* WO 2014/195691 A1, **2014**.

R5. A.J. Bissell, **C.R. Pulham** and D. Oliver, "Strontium Bromide Phase Change Material", *Granted patent* WO 2015/025175 A1, **2015**.

R6. A.J. Bissell, D. Oliver, **C.R. Pulham**, E.J. Goddard, G. Odling and K. Fisher, "Metal Nitrate Based Compositions For Use as Phase Change Materials", *Granted patent* WO 2020/074883 A1, **2020**.

4. Details of the impact

Based on the new stable formulation of salt hydrate PCM developed by EaStCHEM Professor Colin Pulham, *Sunamp Ltd* has brought to market the world's first commercially viable residential heat batteries, allowing the company to grow quickly to reach worldwide orders worth GBP50,000,000. In homes, *Sunamp* heat batteries maximise the use of locally generated renewable energy and off-peak electricity and increase energy efficiency, thereby reducing carbon emissions and saving households money. Installations in social housing properties have shown the particular benefit that heat battery use brings to residents at the greatest risk of fuel poverty, and given social housing providers a valuable, low-maintenance solution for decarbonisation.

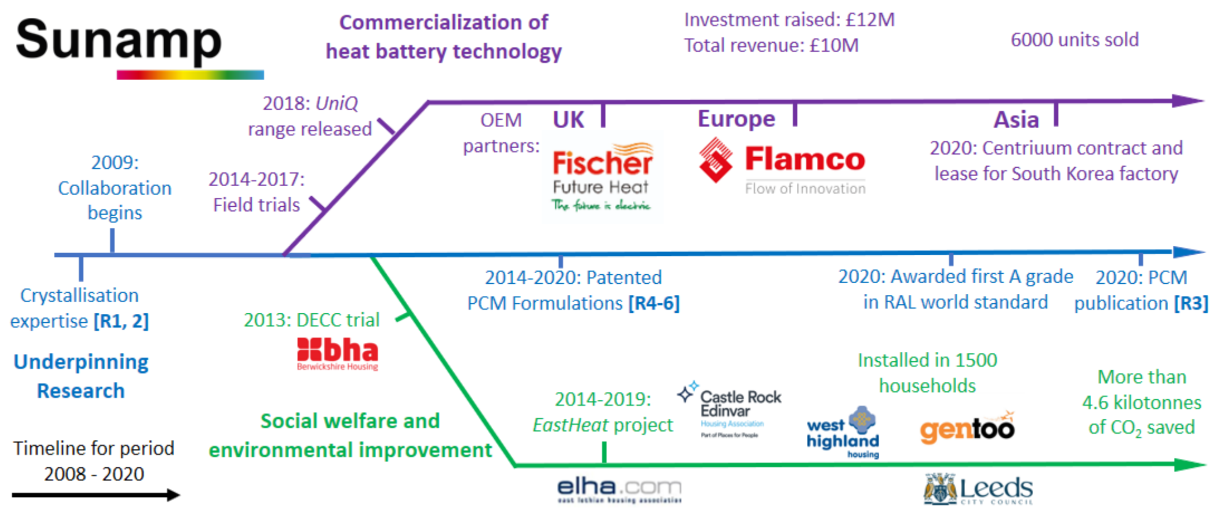

Figure 1. *Timeline showing development of impact from the underpinning research described in Section 2 (blue lines/text refer to outputs referenced in Section 3)* ***[S1]***.

Economic and commercial impact of the world's first commercially viable PCM-based residential heat battery

Based on the patented formulation for SAT PCM **[R4]**, originating from Pulham's research, *Sunamp Ltd* has developed the world's first commercially viable residential thermal energy storage systems (i.e. heat batteries). The company attributes this achievement in large part to the EaStCHEM research that allowed them to "*harness the potential of salt hydrates as a heat store*", confirming that "*Sunamp would not exist without Pulham's research*" **[S1, p10]**.

Sunamp's residential heat batteries **[S2]** (typical installation shown in Figure 2) provide efficient, high density heat storage with an advertised lifetime of over 50 years and at a cost that is competitive with conventional systems – all properties that stem from EaStCHEM research to enable the long-term stability of salt hydrate PCM and reduce its cost **[S1, p4-5]**.

Since August 2013, *Sunamp* has grown rapidly from development of the early *SunampPV* model, primarily deployed in large UK trials from 2014 (1,000 units sold) **[S1, p4]** to full commercialisation of the *UniQ* model, available worldwide since 2018 (5,000 units sold to 12-2020, 20% beyond the UK) **[S1, p9]**. The resulting economic success for *Sunamp* includes the following **[S1, p6-7]**:

- Total investment of GBP12,000,000 raised
- Total revenue of GBP10,000,000
- A twelve-fold growth in orders between 2019 and 2020 – and a current order book worth GBP50,000,000, despite the impact of the Covid-19 pandemic. Major purchase orders have been signed with partner companies in the UK, Netherlands, France, Germany and South Korea (Figure 1).
- Agreement, in 2020, for the lease of a factory in South Korea, with an annual capacity to produce up to 60,000 units, which will meet initial demand from Asian markets.

Figure 2. *Sunamp heat battery (right), showing space saved compared to traditional hot water cylinder (left).*

Sunamp has created 52 jobs (headcount: 52; FTEs: 50) **[S1, p8]**. Economic benefit extends to more than 60 distributors, resellers and installers across the UK, along with partners in the UK, Europe and South Korea who distribute *Sunamp* products under their own brands **[S1, p6-7]**. Partner *Fischer Future Heat* confirms the technology as a "*must have*" hot water solution, providing capabilities unique within the market and popular with customers, and credit its role in driving their business growth and maintaining a strong market position even through the economic challenges of 2020 **[S3]**.

Grant funding of GBP7,700,000 to *Sunamp*, underpinned by further PCMs developed through Pulham research, has enabled the company to extend their technology into new applications **[S1, p11]**. These include automotive (business unit since 2018, developing heat management innovations for engine warm-up, cabin heating, and electric vehicle range consistency) and commercial/industrial applications (business unit since 2019, for greater control, reliability and security of supply and recovery of waste heat) **[S1, p11-12]**. *Sunamp* also worked with Pulham to respond to the Covid-19 pandemic; in 12-2020, *Sunamp* brought to market the *Permafrost VacSafe*, providing long-lasting -70°C storage for the distribution of vaccines **[S1, p12]**.

Environmental and economic benefit through the use of heat batteries

For domestic users, *Sunamp* heat batteries provide highly efficient heat storage and enable increased use of locally generated renewable energy and off-peak electricity, thereby reducing use of conventional fossil energy sources and carbon emissions and saving households money.

Sunamp heat batteries greatly reduce heat loss compared to traditional hot water cylinders. Analysis of the emissions saved through this effect, across all devices installed to the end of 2019, shows that 4.6ktCO_2 have been saved as of late 2020 **[S5, p9]**. For each device, this is a saving equivalent to 26% of the UK annual per capita residential emissions **[S5, p10]**. Even taking into account the carbon footprint arising from manufacture of the heat batteries, all devices installed to the end of 2018 have achieved carbon payback and a net reduction in carbon emissions **[S5, p9]**. Reduced heat loss also saves homeowners money on bills – in trials, a saving of GBP67 per year for every household **[S4, p6]**.

In homes previously struggling with inefficient heating from electric boilers and wet radiators, *Sunamp* heat batteries have delivered a steady supply of heat charged almost entirely with off-peak electricity **[S4, p10]**. This has increased comfort and reduced the need to overheat, resulting in 35% reduction in energy usage **[S4, p32; S4, p79]**. *Sunamp* heat batteries have also been installed in combination with solar photovoltaics (PV) to displace gas burn in a combi boiler, providing between 55-63% of hot water free of charge **[S4, p10]**.

Ultimately, Sunamp heat batteries offer an energy-efficient, affordable and fully controllable route by which households can move to all-electric and renewable energy solutions, providing an immediate viable alternative to the use of fossil fuels for heat. They can be easily retrofitted to decarbonise heating in existing housing, and provide the enabling technology needed to introduce heat pumps to existing properties without excessive, costly and impractical insulation. With heating and cooling consuming almost half of total energy use in the UK, and more than 80% in every home, heat batteries can make a major contribution to reducing CO_2 emissions.

Reduced fuel poverty and operational improvements for social housing providers
Sunamp's work with UK housing associations, which has seen heat batteries installed in 1,500 properties since August 2013 **[S1, p6]**, has shown the particular benefit that heat battery installation brings to residents experiencing fuel poverty. Fuel poverty affects around 4.5 million households in the UK, with residents struggling to pay bills, unable to maintain comfortable temperatures in their homes, or unable to use heating or hot water at all.

Testimony from residents who have received *Sunamp* heat batteries confirms the improvement to their quality of life: *"It saves a lot of money, put it that way. You're getting your hot water for free. Before that, this house was a really cold, cold house…It makes a lovely difference."* (Figure 3) **[S6]**.

Figure 3. *Housing association resident and heat battery recipient Joan, who has noted valuable savings and increased comfort* ***[S4, p20; S6]****.*

Castle Rock Edinvar housing association, who have had *Sunamp* heat batteries installed in hundreds of properties, confirms their significance as a "*genuine solution to fuel poverty*" **[S7]**. The association has also seen multiple other improvements to their operations as a result of heat battery installation. Reduced heat loss helps them meet statutory obligations under the *Energy Efficiency Standard for Social Housing*. In addition, with both gas safety checks and legionella testing no longer required when heat batteries replace gas boilers and water tanks, money is saved as well as safety increased **[S7]**. This is a valuable contribution to mitigating the cost burden of compliance – their biggest growth area in expenditure **[S7]**. *Castle Rock Edinvar* also confirms the important influence that the availability of *Sunamp* heat batteries has had on their strategic thinking around decarbonisation, providing "*a solution for future legislation*" and technology to "*disrupt our approach in a safe way*" **[S7]**.

5. Sources to corroborate the impact

S1. Letter from CEO of *Sunamp*. Confirms underpinning role of EaStCHEM research and resulting economic, environmental, and social benefit.
S2. Brochure for *Sunamp UniQ* range. Confirms commercialisation of product and key properties. https://www.sunamp.com/wp-content/uploads/2018/11/Uniq-Brochure-V1.pdf
S3. Letter from *CEO* of *Fischer Future Heat.* Confirms economic benefit to *Sunamp* partners.
S4. **a)** EastHeat Interim report https://www.sunamp.com/wp-content/uploads/2019/04/Eastheat-Interim-report.pdf **b)** EastHeat case study presented to APSE Energy, 2016 http://www.apse.org.uk/apse/assets/File/John%20Conway%2C%20Edison%20Energy%20%26%20Joan%20Pisanek%2C%20Sunamp.pdf. Confirm carbon and financial savings.
S5. "Sunamp Embedded and Operational Carbon Savings from 2013 to date", Rosales Ortega and Thomson (2020). Report presenting life cycle analysis of Sunamp heat batteries and analysis of carbon savings by devices installed (2015-2019). Confirms carbon saved.
S6. "From hand-warmer to house-warmer for tech firm". BBC News website article, 08-06-2017. Confirms financial savings and increased comfort for residents who received heat batteries. https://bbc.co.uk/news/uk-scotland-40188414
S7. Letter from Director of Business Strategy, *Castle Rock Edinvar* housing association. Confirms benefit to housing association through access to *Sunamp* heat battery technology.