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Ultra-High Temperature Thermal Energy Storage. Part 2: Engineering and operation

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Abstract

The storage of energy at ultra-high temperatures offers many benefits including high energy density and efficient conversion to and from electricity that can be further enhanced by cogeneration. In addition to this, an Ultra-High Temperate thermal energy Storage (UHTS) system would be clean, closed, and reversible and could be built with abundant low cost materials. However, operation at ultra-high temperature is challenging due to the reduced strength and increased reactivity of materials. This paper discusses how a storage system with useful performance can be engineered. In many cases UHTS components and systems can be created by using existing techniques, but in some areas there are engineering challenges that need to be solved before UHTS can become operational. Once the technical and practical feasibility is investigated, there is a brief assessment of the likely capital cost of implementing the storage system at grid scale. As a compact and closed system, UHTS would be inherently suitable for supplying heat at the point of demand. This offers an opportunity to increase the effective roundtrip efficiency to 95%, which far exceeds most other storage methods. Beyond this UHTS could be used to aid the transition of a national energy system to all electric renewable operation. The paper closes with a discussion of the complexities and opportunities brought about by the flexibility of configuration and the transient thermal nature of UHTS.

Keywords

Thermal energy storage electric heat co-generation engineering operation

1.1. Introduction

This paper describes how an Ultra-High Temperature Thermal Energy Storage system could be engineered and is written to support a paper titled "Ultra-High Temperature Thermal Energy Storage. Part 1: Concepts" which will be referred to here as Paper 1. In Paper 1 the Ultra-High Temperature thermal energy Storage (UHTS) concept is described. UHTS offers many benefits over other storage techniques. However to harness the advantages of the UHTS concept it must be practical for real world deployment. This paper demonstrates the feasibility of UHTS whilst outlining the engineering questions that still need to be resolved before the technology can be operational. The configuration of the structures used to store and collect energy is discussed in Section 2.1. Section 2.2 describes the engineering of the heat pump used to recover lost energy. This section will include a thermal analysis that shows how a heat exchanger capable of transferring the required amount of energy can remain within the space and power loss limits necessary for a practical storage system. Section 2.3 will highlight the construction of the charging and extraction equipment. In Section 2.4, an attempt is made to assess the likely capital cost of a UHTS plant relative to other energy storage technologies.

The usefulness of UHTS as an electric-to-electric storage method is demonstrated in Paper 1; however, this usefulness can be further enhanced by the inherent suitability of UHTS to supply heat at the point of

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consumption. In Section 3.1 there is a discussion of how UHTS, integrated with cogeneration, could not only form the centrepiece of a renewable energy system providing electricity, heat and fuel, but could also help a national grid transition from one energy economy to another. The complexities of designing and operating a UHTS plant are discussed in Section 3.2. A summary of the findings of this paper are given in Section 4.

2 Engineering an ultra-high temperature thermal energy storage system

This section will demonstrate how a UHTS plant with a useful level of performance can be engineered whilst remaining both geometrically and financially feasible.

2.1 Storage system engineering

The first engineering consideration for an energy storage system is the medium used to hold the energy and how it is contained. For thermal storage, there is also a requirement to configure this vessel to minimise thermal losses. The standard container material for molten aluminium is alumina (Al_2O_3), which is chemically inert with aluminium [1]. The containment of liquid metal at the temperature and scale required for UHTS is already common in the ore smelting industry, where 20,000 ton furnaces are in use [2]. The outer collector stages for the plant described here will be at lower temperatures and can therefore use lower-cost materials such as crushed rock for the storage medium, and steel for the containment structure.

Conductive losses from the storage vessel can be minimised using medium vacuums. Vacuum insulated panels that can maintain a medium vacuum for decades are in common use at lower temperature ranges [3]. These panels achieve a thermal conductivity of 0.008 W/mK with a vacuum of 20 Pa whilst supported by a silica medium with an average pore diameter of 0.3 mm [3]. Conductive losses for a planar surface is given by Equation 1, where k is the thermal conductivity, A is the surface area, d is the thickness, T_1 is the lower temperature, and T_2 is the higher temperature.

$$P_c = \frac{kA(T_2 - T_1)}{d}$$

Equation 1

From a 24 m spherical UHTS storage core, operating at 1800 K with an external temperature of 300 k with a 0.1m thickness of conductive insulation, the power loss is 0.21 MW compared to the radiative loss of 39.4 MW calculated in Paper 1. This calculation is made using the thermal conductivity value for a panel discussed earlier. Alumina at 1800 K has a conductivity four times higher than a silica filler material at 300 K. However, even if this increased heat transfer by an order of magnitude conductive losses would still be small compared to radiative emissions.

A vacuum insulated panel consists of a medium vacuum contained within a metallic sealing envelope supported by a microporous filler medium [3]. In the context of UHTS the sealing envelope would need to be made from a film of a temperature resistant metal or alloy like platinum-iridium to have the necessary mechanical properties at UHTS temperatures [4]. The filler could be made using an alumina ceramic microporous medium which is available with average pore diameters below 0.3 mm [5]. It has been observed that metallic oxides have an oxygen dissociation pressure which can cause a vacuum to be broken at elevated temperatures [6]. If alumina is used as a filler medium oxygen dissociation will not occur as the associated oxygen dissociation pressure is $1.01325\text{x}10^{-7}$ Pa at 1800 K [7]. Carbon foams [8] are also a candidate for a filler material at elevated temperatures. The metallic envelope can also be used to provide a radiative barrier as discussed below.

Only a relatively small area of solid material is required to support the structure, resulting in negligible conduction losses as demonstrated in Paper 1. The radiative losses can be minimised by reducing the surface area and emissivity of the storage vessel. This dictates that the container should be as close to spherical as possible with a low emissivity outer surface material. A cylindrical vessel is the common shape used in existing furnaces [9] and may reduce the difficulty and cost of engineering the UHTS plant. The disadvantage of a cylindrical shape over a sphere would be to increase radiative losses by approximately 15%.

Alumina offers a relatively low emissivity of 0.69 at 600 K and 0.41 at 1400 K [10]. However, it may be possible to coat the alumina containment vessel in a low emissivity metal such as platinum, gold or tungsten.

Platinum is the most suitable material to coat the storage core as it has an emissivity of 0.047 at 373.15 K and 0.191 at 1773 K [11]. It is common to splutter coat platinum onto an alumina substrate [12]. With only a 300 nm thickness coating of platinum required to lower the emissivity [13] of the storage core, the cost of this small amount of rare metal (1.5kg for coating a 24.3 m sphere) is negligible compared to the energy savings the coating confers. If vacuum insulating panels were used as a combined radiative and conductive barrier a metallic film with a thickness of 100 µm would be required to resist mechanical loading [3]. If this barrier was made of platinum the cost would be approximately $US 14.7 million.

The platinum coating will be protected by the medium vacuums put in place to minimise conductive losses.

The construction of the storage vessel and its support structure can be achieved with conventional furnace building techniques. It should be possible to create the spherical storage container required for UHTS using shaped monolithic bricks and existing construction methods [9]. Molten metal is contained by lining the inner surface of the monolithic brick vessel with a refractory mastic to provide a seal [9].

UHTS is a closed system where pure aluminium can be used; therefore, all the following factors that reduce furnace life span can be eliminated:

- Mechanical damage during the loading process.
- Damage to the lining due to impurities in the molten metal.
- Erosion caused by the flow of molten metal during unloading.

Without these causes of damage the usual ten years of use a large furnace gets between relining [14] could be extended almost indefinitely for a UHTS vessel. Creep could be a limiting factor on UHTS core container lifespan; however, as creep in ceramics is well understood [15] it can be minimised by design. Thermal shock and differential expansion may limit the charge and discharge rate of the UHTS plant, but again thermal shock resistance of ceramics is predictable and well understood [15], and methods to allow differential expansion in furnaces without damage have been developed [9, 16].

Whilst the metal storage medium is solid it will expand and contract as it is heated and cooled. If the medium remained solid during the complete temperature range of the storage system then appropriate spacing could be left to account for expansion. However, when the metal is liquid at some stage during operation this is not possible. In this scenario, when the medium is reheated material expansion may lead to damage of the UHTS vessel. To avoid this damage a controlled melting process must be implemented for use during the charging cycle. Vacuum remelting furnaces [17] remove impurities by reheating metals solidified within a container. This is accomplished through a controlled melting process, which avoids the expansion that would lead to vessel damage during reheating. If a controlled melting process cannot be adapted for use within a UHTS plant, it will be necessary to operate with a material that remains solid through the full temperature range, which will have implications for plant size and thermal loss rates.

2.2 Storage cycle heat pump engineering

The heat pump that is described in the first paper is a non-essential system that could be added to the UHTS plant to recover energy during the storage and charge cycle. The alternative method of energy recovery discussed in paper 1, which may be simpler to implement, is the use of storage stages to collect lost heat that can then be used for gas heating during the extraction cycle. The use of a heat pump within the UHTS charging cycle makes the operation of the UHTS plant similar to existing pumped heat systems like those described by McTigue et al.[18], Desrues et al.[19], morandin et al.[20] and Thess [21]. These pumped heat concepts share the components seen in the UHTS heat pump like the heat exchangers, compressor and turbine but are intended to operate within a temperature range from 123K to 1268K. Therefore, previous authors have not addressed the engineering difficulties introduced by ultra-high temperature operation.

The critical components of the heat pump used to return escaped heat to the storage core include the compressor, turbine and the heat exchangers. The multi-stage compressor of the heat pump operates with a total pressure rise and flow rate seen within a portion of a conventional turbojet compressors (2.8 and 55.4 kg/s), but at a higher temperature. The temperatures (1900 K) and blade loadings present in the compressor of the UHTS heat pump are comparable with those experienced by the turbine blades in conventional turbojets [22]. Therefore, the UHTS heat pump compressor would need to use the same blade material [23], cooling [24] and surface coatings [25] found in the turbines of a conventional ABGT.

The heat pump operates on a nitrogen closed cycle [26]; therefore the working fluid can be controlled, leaving it free of particles and the reactive combustion chemicals that reduce the operational life of ABGTs.

One possible material for the compressor blades and stators is nickel super alloy [24]. Nitriding of super alloys can be reduced by adding small amounts of oxygen to the nitrogen [27], or with ceramic barrier coatings [25]. It should also be noted that if metal compressor blades were used cooling would be required to maintain mechanical integrity at elevated temperatures resulting in a significant power loss in the cycle [28]. In a conventional ABGT this low temperature gas is bled from a stage within the main compressor, and then passed through the interior of each turbine blade, before emerging from holes in its surface to provide cooling to the blade. For an ABGT operating with a turbine entry temperature of 1900 K, a compression ratio of 24 with barrier coatings, and film cooling applied to a single turbine and diffuser, the proportion of the air bleed from the main compressor is 9% [29, 30]. This assumes a blade cooling technology is used from 2005 with internal cooling efficiency of 70% and a film cooling effectiveness of 40% [30]. For a UHTS heat pump the energy cost of operating the compressor calculated in Paper 1 is 39.4 MW. Considering there are six compression stages and at least one turbine stage that will require cooling, the heat pump would require an estimated 25 MW to maintain the mechanical integrity of the turbomachinery. It should be noted that this approximation does not account for the difference in gas properties and operating conditions between an ABGT and a heat pump. To properly assess cooling requirements for the UHTS heat pump a complex numerical model would be required, like the one presented by Wilcock et al [30]. If 25 MW were required to cool the turbomachinery it would significantly reduce the economic viability of implementing a heat pump within a UHTS plant. It is likely that even with more advanced technologies such as transpiration cooling that the air bled from the main compressor could not be reduced to a viable level [29]. Therefore a second option that may be attractive for the UHTS heat pump compressor is an uncooled ceramic construction which may have fewer disadvantages in a closed cycle UHTS heat pump than in an ABGT. The main factors that limit the use of ceramics in ABGTs are water vapour erosion, combustion product reaction with blade material, and foreign object damage [31], all of which are absent in the UHTS heat pump.

The rotating turbomachinery components of the heat pump would be subject to the highest temperatures and loads within the engine. In addition, other components need consideration due to their high operating temperatures including the casing and bearings. The casing would be operating close to the maximum temperature of the working fluid (1900 K) but would only be loaded by the pressure of the gas and the structural requirements of the turbomachine. Therefore it would need to be made of an engineering ceramic if uncool or a cooled high temperature metal like those discussed above for the making compressor blades. The casing cooling requirement would be less than for the compressor blades due to the lower loads but may still be significant. To make a casing from an engineering ceramic is technically feasible but has not been attempted and therefore may be economically unfeasible. The rotating motion of the turbomachinery must be supported by bearings; in turn these bearings must be cooled and lubricated with oil [32, 33]. To avoid auto-ignition the oil temperature must remain below 550 K [34]. In many gas turbine designs the bearings are enclosed in a chamber that is in close proximity to the high pressure and high temperature turbines [34]. The heat pump in UHTS will also require bearings and therefore sufficient oil will need to be provided for their cooling and lubrication. The need to cool this oil will represent an additional energy loss in the heat pump. In a conventional ABGT only a small part of the engine operates at ultra-high temperatures. Conversely, in the UHTS heat pump the entire compressor and turbine operate at these elevated temperatures. However, to reduce size and weight in a conventional ABGT each stage of the compressor and turbine must be sequentially arranged on a shaft which drives the need for some of the bearing chambers to be in close proximity to the high temperature regions of the engine. In the UHTS heat pump these limitations do not exist so it may be possible to separate the compression stages and support the shafts at more remote locations, lowering cooling requirements.

The main difference between a conventional ABGT compressor and the UHTS heat pump compressor is the inter-stage heat exchangers used to transfer heat to the storage core. In the UHTS heat pump compressor, nitrogen is ducted from each compressor stage through a manifold to a heat exchanger where the gas transfers its heat to the storage medium. The working fluid is then routed into the following compressor stage, as shown in Figure 1. This configuration has similarities with the protruding silo-type combustors used in some industrial gas turbines [35].

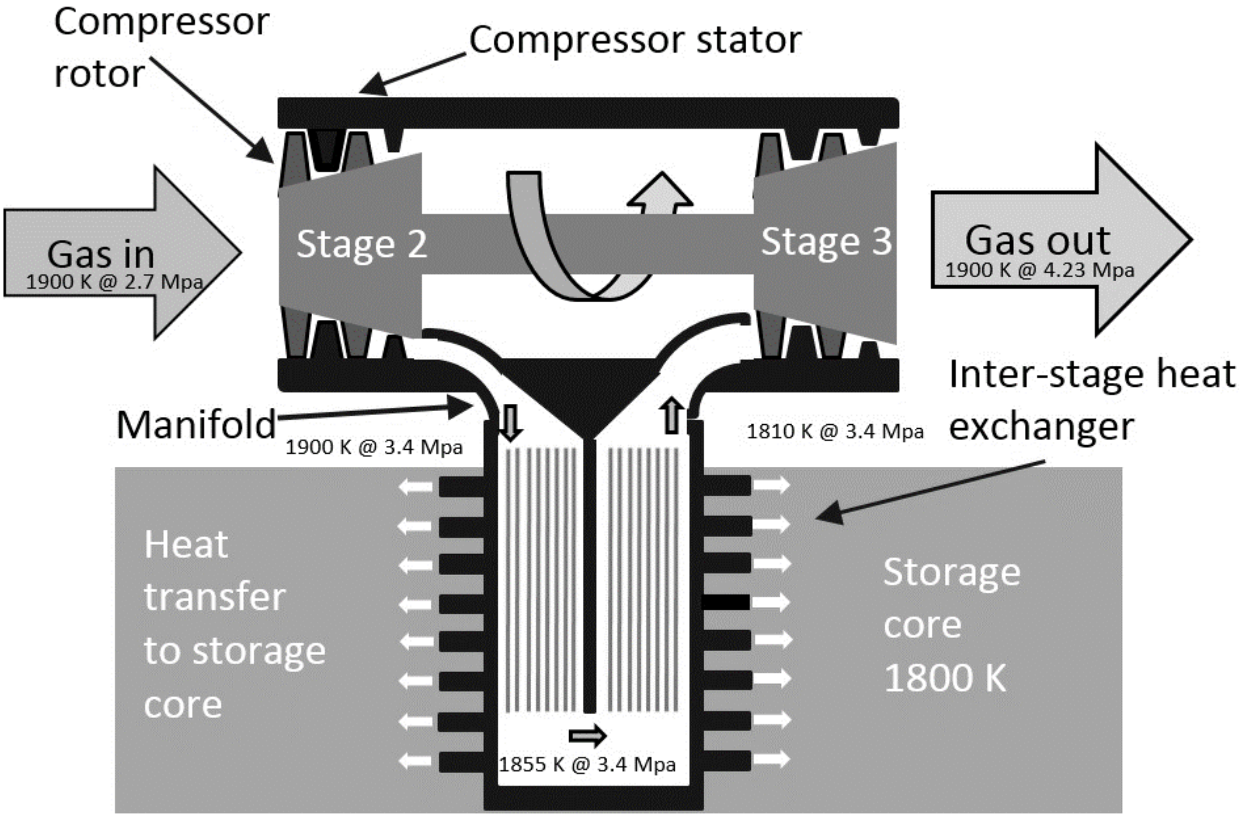

Figure 1 Configuration of second and third stage compressor including inter-stage heat exchanger.

In storage mode each of these heat exchangers has to transfer energy at a rate of 6.58 MW (39.4 MW in six stages) by cooling 43.1 kg/s of nitrogen from 1900k to 1810 K. Using heat exchangers within gas turbine cycles is a well-established idea with recuperation offering substantial improvement in fuel consumption [36]. These heat exchangers collect heat from the gas after it exits the turbine and use it to preheat the air entering the combustion chamber. Although recuperation has been proven beneficial in aircraft engines, it has not seen widespread adoption in the aviation industry due to the additional weight involved [36]. Recuperation is commonly used for power generation [37] and in marine applications [38]. Metallic heat exchangers are proposed for gas temperatures up to 1000 K. Beyond this ceramic [39] or carbon-carbon composites [40] are viable options. Ceramic recuperators are expected to give a reasonable service life in aircraft turbojets up to 1600 K [39, 41]. When compared to the UHTS application, gas turbine recuperators exist in a more difficult environment where corrosion by water vapour or combustion products is a factor [40]. Recuperators are also gas-to-gas heat exchangers and are therefore more complicated than the gas to highly conductive solid/liquid heat exchangers required for UHTS and will not have the joining and sealing issues of ceramic gas-to-gas recuperators [40].

Another area where comparable heat exchangers are used is in volumetric sunlight receivers in solar thermal power plants [42]. These ceramic [43] solid to air heat exchangers operate at ultra-high temperatures [42] and transfer the energy from concentrated sunlight to a gas, which can then be used to generate electricity through a turbine. A common receiver material is silicon carbide, which can be formed into the monolithic honeycomb structure shown in Figure 2 using direct extrusion [43, 44]. The upper operating temperature of silicon carbide receivers is stated as between 1673 K [43] and 1773 K [42].

Volumetric receivers experience more difficult conditions than the UHTS heat-exchanger as they are subjected to chemical attacks from oxygen [43] and water vapour.

Moving into the future, ultra-high temperature ceramics like zirconium diboride may have the required mechanical properties for the UHTS application at temperatures between 2100–2700 K [45]. Zirconium diboride has also been processed into monolithic honeycomb using extrusion [46].

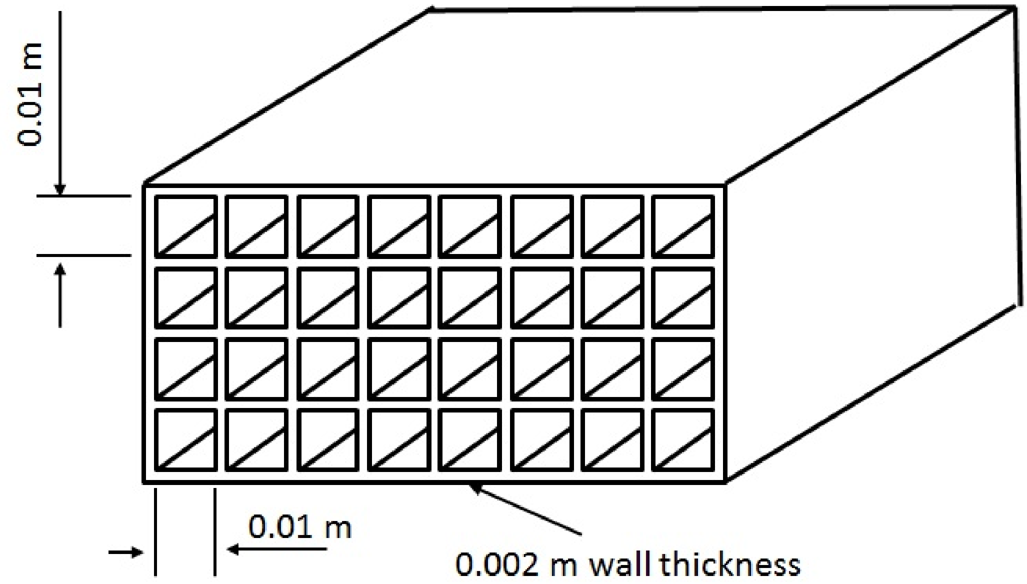

Figure 2 Portion of monolithic ceramic honeycomb heat exchanger.

The monolithic honeycomb structure would act as the basic gas to solid heat transfer element for the UHTS inter-stage heat exchanger. In addition to this honeycomb, the heat exchanger would require solid elements to ensure proper distribution of heat to the storage medium. The feasibility of the UHTS inter-stage heat exchanger can be verified first by considering a single duct within the honeycomb shown in Figure 2. The flow condition in the duct can be assessed using Equation 2:

$$Re = \frac{\rho u D_h}{\mu}$$

Equation 2

Where ρ is density, u is the velocity, μ is the dynamic viscosity and the hydraulic diameter (D_h) of the duct is the characteristic length. The velocity in the duct is calculated by first finding the bladed area of an existing comparable ABGT (Mitsubishi J 501g) then scaling it by mass flow rate of the UHTS heat pump. This results in a flow cross sectional area of 0.065 m^2 for the first stage UHTS compressor. As the nitrogen passes from the compressor to the heat exchanger, it is expanded by a factor of six to lower the flow velocity and reduce energy losses through the honeycomb. The heat exchange cross-sectional area is then divided by the inlet area of the individual duct to give the number of ducts required to maintain the flow path area. For 43.1 kg/s of nitrogen to pass through the heat exchanger without compression at a velocity of 6.74 m/s, 2703 ducts are required. The Reynolds number in each duct is found to be 4315, and is therefore treated as fully turbulent with a negligible entry length [10].

The nitrogen exit temperature (T_e) from the single square duct can be calculated using Equation 3:

$$T_e = T_s - (T_s - T_i)\, exp\left(\frac{-hA_s}{\dot{m}c_p}\right)$$

Equation 3 [10]

Here T_s is the surface temperature, T_i is the inlet temperature, h is the convective heat transfer coefficient, A_s is the surface area of the duct, and $\dot{m}$ is the mass flow rate. The surface temperature is consistently maintained at the storage medium temperature, as silicon carbide in contact with liquid metal has a much greater heat transfer coefficient than the gas in the duct. The convective heat transfer coefficient h is calculated using Equation 4:

$$\boldsymbol{h = \frac{k}{D_h} Nu}$$

Equation 4

Here $\boldsymbol{k}$ is the thermal conduction of nitrogen and $\boldsymbol{Nu}$ is the Nusselt number, which is found using the Dittus-Boelter equation:

$$\boldsymbol{Nu = Re^{0.8} Pr^{n}}$$

Equation 5

In Equation 5, *n* is 0.3 as the gas is cooled. Prandtl number Pr and the other fluid properties required to complete the above calculations (k, μ, v, ρ, c_p) are read from the relevant thermodynamic tables [10, 47].

When Equation 3 is solved for the UHTS heat exchanger it is found that the individual ducts need to be 4.5 m long to transfer sufficient energy to reduce the nitrogen temperature from 1900 K to 1810 K. As a result the full heat exchanger would have an inlet area of 0.39 m^2 and a length l of 4.5 m, which has little effect on the 7513 m^3 storage volume of the UHTS system.

The flow power loss P_{he} of passing the nitrogen through the heat exchanger is assessed with Equation 6 and Equation 7:

$$P_{he} = \dot{V} \Delta P_l$$

Equation 6

$$\Delta P_l = f \frac{l}{R_a} \frac{u_{avg}^2}{2}$$

Equation 7

Where $\dot{V}$ is the volume flow rate, u_{avg} is the average velocity in the channel and ΔP_l is the pressure loss in the heat exchanger. The Darcy friction factor f is referenced from the Moody chart using the Re, and the $R_a$is the roughness height of extruded silicon carbide honeycomb, which is 0.1 µm [48]. The approximate power loss of each inter-stage heat exchanger using Equation 6 and Equation 7 is 0.013 MW and represents 0.2% of the heat transferred after the gas has passed through all six heat exchangers. This loss can be further decreased at the cost of increasing the volume of the heat exchangers. As a result, the storage cycle inter-stage heat exchanger is feasible in terms of both space and power consumption.

This analysis does not consider the arrangement and flow path of the heat pump. Heat exchangers have been successfully integrated within gas turbines without excessive pressure drop [49] including intercooling between compressor stages [41].

2.3 Extraction and charging cycle engineering

The direct electric charge equipment for UHTS would be engineered in an identical way to existing arc, resistance or induction furnaces. The charging heat pump is made in the same way as the pump described in Section 1.2 but would need to be twenty-six times larger than the storage cycle pump to achieve the fast charge discussed in Paper 1. At this size, the heat exchangers would be feasible and require only 0.5% of the storage core's volume. The extraction cycle is almost identical to existing combined cycle gas turbines, except heat exchangers are used in place of combustors. The heat exchangers used in the extraction cycle would be engineered in the same way as with the heat pump inter-stage heat exchanger discussed in Section 1.2, but with greater consideration for oxidation resistance.

2.4 Capital investment cost

It is difficult to assess the capital cost of a UHTS plant at this early stage of technological development; however, the material and equipment can be evaluated based on historical data to give an estimate of how much UHTS might cost compared to other storage technologies.

Table 1 was compiled by assessing the raw material costs for the UHTS configuration shown in Paper 1. The mass of the alumina support structure is estimated to be 25% of the mass of the aluminium storage medium used. The masses of the outer collector stages and containers are scaled to 25% of the storage core, with the storage container for each of stage set at 25% of the contained thermal mass.

Table 1 [50]

Component	Material	Mass (kg)	USD$/kg	Cost (USD$ x10^6)
Storage core	Aluminium	24800000	1.59	39.4
Core container	Alumina	6200000	0.25	1.6
Thermal barrier	Platinum	500	29300.00	14.7
Stage 1 thermal mass	crushed rock	6200000	0.03	0.2
Stage 1 container	Alumina	1550000	0.25	0.4
Stage 2 thermal mass	crushed rock	6200000	0.03	0.2
Stage 2 container	Alumina	1550000	0.25	0.4
Stage 3 thermal mass	crushed rock	6200000	0.03	0.2
Stage 3 container	Stainless steel	1550000	0.50	0.8
Total				57.7

Another critical part of the storage system is the heat pump. This heat pump has many similarities to a large gas turbine. The heat pump has a mass flow rate of 1420 kg/s when charging: General Electric GE90 has a mass flow rate of 1350 kg/s and costs US$27.5 Million [51]. By combining the heat pump cost with that of the storage and containment material an estimate of the minimum price of a UHTS plant can be found in Table 2. It is not possible to assess fabrication costs without detailed designs; however even at a total cost nine times greater than the material cost as shown as maximum in Table 2, UHTS remain competitive with other technologies. Blast furnaces [52] are the closest system in terms of configuration, temperature and scale to UHTS plant in operation. The capital cost of a blast furnace capable of containing 6000 m^3 of metal built in a developed western country is quoted at US$700 Million [53]. If this volume was filled with aluminium at 1900K and used for UHTS the storage cost would be US$81 /kWh. The blast furnace use a refractory structure of the kind required for UHTS but without the thermal loss reduction and recovery systems utilised for UHTS. However, the UHTS does not require the material handling and combustion heating equipment seen in a blast furnace. On balance, the capital cost of a UHTS and a blast furnace may be broadly comparable though UHTS should have a significantly lower maintenance cost. The main cost of blast furnace maintenance is repair of damaged refractories, and relining [54]. As discussed in Section 2.1, this does not apply to a UHTS plant due to the closed and inert nature of the containment vessel and storage medium. The other major component that will require maintenance in the UHTS plant is the heat pump, which may have similar maintenance costs to the hot blast and exhaust gas treatment system used in a blast furnace.

The extraction equipment used to recover the heat from the core to electricity is directly comparable to a combined cycle gas turbine plant, which costs US$78.5 Million per 500 MW of generation [55] In Table 3 the cost related to power generation and energy storage is shown for UHTS along with common energy storage technologies.

Table 2 [56-58]

	Capital cost			
	US$/kWh (electric-to-electric storage)		US$/kW (electric-to-electric storage)	
Technology	min	max	min	max
Pumped Hydro	5	100	600	2000
Compressed air	2	50	400	800
Hydrogen fuel cell	0	35.5	745.5	10000
Redox flow battery	150	1000	600	1500
lead acid battery	200	400	300	600
Li-ion battery	300	600	600	1200
UHTS	7.9	70.8	156	234

From this analysis, it is clear that UHTS is likely substantially cheaper than other storage technologies in terms of installed power. When storage cost is considered, UHTS could be competitive with mechanical methods and superior to batteries. This capital cost analysis does not account for the many other price differences in storage technologies such as maintenance, length of service and disposal.

3. Energy system integration: Opportunities and complexities

In this section, a discussion of how UHTS can be used to supply heat and electricity at the point of demand will be provided, followed by a note on the complexities resulting from the transient nature of UHTS and its flexibility of configuration for different deployment scenarios.

3.1 UHTS: A total energy system

Thus far, UHTS has been discussed as a standalone technology for electric-to-electric storage; however its closed and safe nature makes it very attractive for cogeneration and trigeneration. Fuel-burning cogeneration plants have achieved overall efficiencies of up to 95% [59] but emit by-products into the local environment. UHTS can offer the same efficiency whilst using a closed extraction cycle [26]. Even if an open extraction cycle were used, atmospheric air would pass through heat exchangers unchanged and unpolluted. This means that UHTS would be more attractive than combustion-based open cycle generation technologies in areas close to residential and commercial heat demanded.

A UHTS plant bears many similarities to large aluminium melting furnaces and smelters in terms of safe and unobtrusive operation. These extractive metallurgy facilities are commonly built between 50 m and 500 m from residential areas and have been used to supply heat and electricity [60, 61]. Additional safety could be provided with a subsurface concrete container to catch the core storage medium in the case of a vessel failure. Concrete containers that extend below ground are a standard safety feature of nuclear reactors [62].

The storage-stage architecture enables the possibility of supplying heat at different temperatures to different processes. One process that benefits from a supply of heat is hydrogen production. Increasing the temperature of water in electrolysis reduces the electrical energy required to produce hydrogen[63]. This offers both a transportation fuel and an opportunity for seasonal storage once the UHTS extraction cycle is configured to use combustion heating. However, the addition of switchable combustion heating to the UHTS plant might reduce the attractiveness of deployment close to residential and commercial areas. Electrolysis of carbon dioxide and water can also be used to produce a natural gas substitute [63]. With the addition of carbon capture [64], plant emissions could be reduced whilst providing CO_2 for the next electrolysis cycle.

The ability to integrate electric-to-electric storage with gas production and combustion leads to the prospect of UHTS being used as the centrepiece of a total energy system. In addition to this UHTS also offers a means of migrating from one energy economy to another. UHTS can provide heat and electricity at the point of greatest demand, as well as the possibility of supplying hydrogen for transportation and natural gas substitute to existing networks. This is on top of the ability to match electricity and heat supply to demand over hours, days, weeks and the seasons with the thermal storage core, and with power to gas and gas combustion generation cycles. This flexibility also supports a changing electricity grid. In a transition from 0–100% intermittent or cyclic renewable generation UHTS could operate initially as a conventional combustion heated combined cycle power station using a natural gas fuel. Increasingly the thermal core could be utilised with charging by a growing renewable generation sector with seasonal support provided by an existing gas network. As renewables begin to dominate, the UHTS plant would help produce hydrogen for seasonal storage and natural gas substitutes to supply a diminishing gas network. At 100% renewable electric generation, the UHTs would provide electricity and heat whilst supplying hydrogen for transport, in addition to storing energy for seasonal use as hydrogen and short-term use in the thermal storage core.

3.2 Plant configuration and transient operation

In Section 3.1, the inherent suitability of UHTS to integrate with co-generation and future power to gas technologies was discussed. This flexibility leads to several possible plant configurations, beginning with simple electric-to-electric storage and growing in complexity with the addition of district heating, electricity to gas and gas combustion for electricity generation. In addition to configuration the inherent transient nature of the storage plant adds complexity when considering how a UHTS plant may be designed to provide optimum performance in different supply and demand scenarios.

The descriptions of the thermodynamic cycles in each of the three stages of operation given in Paper 1 are single-moment snapshots of a UHTS plant in one possible configuration and are useful to describe and demonstrate a novel idea. However, these calculations are not of the required accuracy for detailed design and simulation of the charge, store and extraction cycles. Nevertheless, as the concept of UHTS develops to the point where a detailed design is required for deployment, the following complexities need to be considered:

- The transience of thermal losses, heat pump nitrogen pressure, heat pump efficiency and extraction efficiency as the temperature of the storage core changes.
- The fact that energy lost from the storage core to the collector stages can be recovered using the heat pump during the charge cycle or to pre-heat air or steam during the extraction cycle. The optimum approach will be dependent on the length of the storage cycle and the thermal mass of the collector stages. It may be that installation of a heat pump is only economically viable in certain circumstances.
- The ideal plant configuration will change dependent on how long and how much heat is used for electricity generation or directly for process and district heating.
- The way in which electricity is supplied to the UHTS plant in both quantity and duration will affect the optimal configuration.
- The distribution of heat between the core and each of the collector stages after each of the charge and discharge cycles will determine the best method of charge and discharge.
- All of the above factors will interact with each other and may have significant effects on the inherent performance, cost and flexibility of the plant.

This leads to the conclusion that although the modelling shown in this paper is useful to analyse and demonstrate the concept of UHTS, a more complex approach is required to conduct the detailed design of a practical system. At minimum, a transient numerical model with the following features is required:

- Realistic supply and demand cases.
- Thermal model of storage core and stages.
- Thermodynamic model of heat pump and extraction cycles.
- A convective and flow model of inter-stage and labyrinth heat exchangers or an accurate representation.

4. Summary

In Paper 1, a novel energy storage technology was described; in this paper there is a demonstration of how the storage system could be engineered. The liquid/solid aluminium storage core could be contained in an alumina vessel made using methods commonly used to build foundries and furnaces. The closed nature of the core and the use of a pure aluminium storage medium would lead to an almost indefinite life for the vessel as long as creep deformation was minimised through design. A majority of the heat pump could be engineered to achieve acceptable service life at elevated temperatures using methods long proven in air breathing gas turbine engines Although the heat pump is shown to be a valuable way of reducing thermal losses in Paper 1, it may only be economically viable in limited situations. This is due either to the high energy cost of cooling conventional metallic turbomachinery components or the capital cost of producing the unproven uncooled ceramic alternative. If the heat pump is not installed in the UHTS plant the extraction cycle can be preheated from the collector stages to recover lost heat.

The extraction and heat pump cycles rely on solid/liquid to gas heat exchangers that can withstand high temperatures. Heat exchangers that operate in this temperature range can be found in volumetric sunlight collectors and gas turbine recuperators. They are commonly made with monolithic honeycomb silicon carbide. This paper demonstrates the ability of suitable heat exchangers to fit within this storage core without a significant reduction in the volume of the storage medium. The flow losses within the heat exchangers are also examined and found to be acceptable. There are significant engineering challenges highlighted within this paper that need to be solved before UHTS could enter service including:

- Adaptation of controlled remelting techniques to avoid damage of storage medium container damage through metal expansion.
- The adaptation of vacuum insulated panels for use at ultra-high temperatures.
- The creation of low energy methods of maintaining mechanical integrity within the heat pump compressor.

The second section ends with a limited assessment of the likely capital cost of a useful Ultra-High Temperature thermal energy Storage (UHTS) plant. This analysis concludes that a UHTS plant could be significantly cheaper than other storage technologies in terms of installed power (US$/kW), and be competitive in terms of storage cost (US$/kWh) whilst maintaining significant advantages in many other metrics of performance.

In the third section of the paper, there is a discussion of the inherent suitability of UHTS to cogeneration and location at the point of demand due to its compact, closed and safe nature. This could offer an opportunity to increase the effective roundtrip efficiency to 95%, which far exceeds most other storage methods. The thermal nature of UHTS, and its integral extraction cycle capable of being switched between gas combustion and direct heating, raises the possibility of a system that will store and supply heat and electricity whilst producing and using combustion fuel. Collectively this then leads to a method of transitioning from one energy economy based on the combustion of non-renewable sources - to one based totally on cyclic and intermittent renewable generation. The third section closes with a discussion of how the configuration of a UHTS plant would be highly dependent on how energy was supplied and used. This complexity leads to the necessity for a transient numerical model to support detailed design or plant configuration.

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