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1-A073A Development of Advanced Solar Thermal Energy Storage Technologies for Integration with Energy-intensive Industrial Processes and Electricity Generation

Final report: project results and lessons learnt

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Executive Summary

Cost-effective thermal storage systems are required if solar thermal energy is to make a significant contribution to Australia's electricity generating sector and to supply the energy requirements of its energy-intensive industries. The development of reliable and effective storage systems for concentrated solar power plants will give them the dispatchability to meet peak demands.

CSIRO and Abengoa Solar New Technologies S.A. have therefore been collaborating on a project designed to demonstrate proof-of-concept of the integration of a solar thermal storage system with a solar energy concentrator/receiver facility to store high grade heat that, at a subsequent commercial scale, could be used on demand by electricity generators and other industrial processes.

The upper temperature limit of existing solar thermal storage systems based on the use of conventional molten salts, such as sodium/potassium nitrates, is 565^{o}C. However, additional opportunities involving higher efficiency power generating cycles, would be created for solar thermal technologies if this upper limit could be significantly extended.

The project therefore involved a number of activities directed at:

1. Evaluating the opportunities for applying solar thermal energy in Australian process and power generation industries.
2. Identifying the most appropriate heat transfer and storage media suitable for high temperature storage applications.
3. Designing, constructing and operating a solar thermal energy storage system, including a suitable solar receiver/absorber, fully integrated with the solar thermal concentrating facility at the CSIRO Energy Centre in Newcastle, NSW. The plant was designed to store 750 kWh of solar thermal energy.

Initial development work was directed at identifying the most appropriate heat transfer and storage media for high temperature solar thermal energy storage applications. This involved a consideration of gases, liquids and solids as potential heat transfer and storage media, including molten salts which can be used as both a heat transfer fluid and a storage medium. It was ultimately decided that the use of a gas (pressured CO_2) as the heat transfer fluid, where the gas is heated in the absorber/receiver and then subsequently transfers its heat to a solid storage medium (alumina balls), provided the best option within the timescale of this project.

The normal operating scheme for this plant was for the Storage Vessel to be charged with solar energy during the day with the hot gas entering at the top and cold gas leaving at the bottom. This charging would continue until the temperature at the top reached 750^{o}C or the outlet temperature at the bottom reached 300^{o}C. The system would then be operated with CO_2 flowing in the reverse direction so that cold gas entering the bottom was heated during passage through the vessel and then sent to a Steam Generator to raise superheated steam.

Operation of the facility has indeed shown that a combination of CO_2 as the heat transfer fluid and alumina balls as the thermal storage medium is a viable combination for high temperature thermal energy storage. However, the performance of the Storage Vessel, that holds the 20 tonnes of alumina balls, has very much been the factor that has limited the performance of the test loop as installed. Heat losses, particularly from the top of the Storage Vessel where the bed temperature is at its highest, were so significant that it prevented the system being operated over charge/discharge cycles from one day to the next. There was also evidence of some level of non-uniform heating across the Storage Vessel in charge mode, as the gas flow channels through the central region of the vessel towards the centrally located outlet at the bottom of the Storage Vessel. It would appear that the bottom gas distributor which was designed to avoid such a problem is not ensuring an even flow of gas down through the Storage Vessel. Discharge of stored heat from the Storage Vessel via the Steam Generator did, however, prove to be very easy to control with steady generation of superheated steam being achieved.

The Receiver/Absorber had to be constructed from a special high temperature alloy because of the high metal temperatures that arise due to the poor heat transfer that occurs when heating a gas of relatively low density (compared to a liquid heat transfer fluid). In addition CO_2 at high temperatures and pressures can be very corrosive of many metal alloys. Indications from our experiments are that provided that the gas can be supplied to the Solar Receiver at its design temperature of around 250^{o}C then it will meet the required duty.

Studies carried out on Australian industrial applications that would benefit from the inclusion of solar thermal storage have indicated the technology is not only affected by the solar availability at the site, but also the scale of implementation. It is likely that the technology is currently only viable on a scale exceeding 100MWe for electricity generation or 250MWt for heat provision. In areas of high to very high solar availability the levelised cost of production of electricity was estimated at $175/MWh and heat production at $14/GJ. While these costs may not currently be attractive in the general market place, some areas of high solar availability in Western Australia, Northern Territory and Central to Western Queensland where other energy supplies can be limited may be potential sites for application.

Figure 1 - The completed 750kWh solar thermal energy loop

Project Overview

Project summary

CSIRO and Abengoa Solar New Technologies S.A. have collaborated on a project designed to demonstrate proof-of-concept of the integration of a solar thermal storage system with a solar energy concentrator/receiver facility to store high grade heat that, at a subsequent commercial scale, could be used on demand by electricity generators and other industrial processes. The development of a reliable and cost effective storage system for concentrated solar power plants will give them the dispatchability to meet reliably bulk and peak demands.

Work was initially concentrated on identifying a suitable combination of heat transfer fluid (CO_2) and heat storage medium (alumina), and was followed by the design of a 750kWh heat collection and storage loop that was connected to a high pressure superheated steam generator. The facility is located at CSIRO's National Solar Energy Centre, Newcastle, making use of the new 1.2 megawatt (thermal) solar field and tower, constructed as part of an ASI Foundation Project. The objective was to operate this facility to demonstrate the viability of the CO_2/alumina system to store solar thermal energy at around 700°C to 750°C and discharge it at a later time to generate superheated steam.

Project scope

Cost-effective thermal storage systems are required if solar thermal energy is to make a significant contribution to Australia's electricity generating sector and to supply the energy requirements of its energy-intensive industries. The development of reliable and effective storage systems for concentrated solar power plants will give them the dispatchability to meet peak demands.

The upper temperature limit of existing solar thermal storage systems based on the use of conventional molten salts, such as sodium/potassium nitrates, is 565°C. However, additional opportunities involving higher efficiency power generating cycles would be created for solar thermal technologies if this upper limit could be significantly extended. In order to encourage the widespread use of solar thermal energy by Australian industry, there is therefore a need to identify, develop and demonstrate solar thermal energy storage technologies that can operate at as high a temperature as can be reliably achieved.

The project therefore involved a number of activities directed at:

1. Evaluating the opportunities for applying solar thermal energy in Australian process and power generation industries.
2. Identifying the most appropriate heat transfer and storage media suitable for high temperature storage applications.
3. Designing, constructing and operating a solar thermal energy storage system, including a suitable solar receiver/absorber, fully integrated with the solar thermal concentrating facility at Newcastle.

The involvement of one of the world's leading solar thermal companies, Abengoa Solar New Technologies S.A., as a collaborator in this project, provided a wealth of background experience and skill that could be input to design of the solar receiver/absorber and the thermal energy storage vessel. For CSIRO this project has provided an opportunity to develop and expand their expertise in this area and to help foster strong international links with overseas researchers and technology developers working on solar thermal energy storage.

Outcomes

Activity 1

An initial study into appropriate Australian industrial applications that would benefit from the inclusion of solar thermal storage identified location, scale of energy use and operating temperature for approximately 2500 sites operating processes in the fields of mining, mineral and chemical processing, building products, textiles and wood products, food processing and electricity generation. These sites represent about 150,000MW in terms of potential demand for primary energy input. While it is evident that most of these sites are not in areas of peak insolation, generally there are sites where solar thermal technologies could provide a beneficial energy input to reduce the consumption of other energy types. It was clear from this study that preferred sites, particularly in the early stages of technology proving, will be those where solar thermal input is in areas of high insolation that have limited access to grid electricity or gas pipelines. However, as the technology develops there will be an increased range of high energy consuming processes that could be targeted.

When these results were revisited in a subsequent study the number of sites was reduced to 92 by only allowing sites that were in areas of moderate or higher solar availability and had a scale and temperature range of operation that was appropriate to the either electricity or heat production from the plant. Despite this reduction, these sites still represent a total primary energy demand of around 5800MW. One other challenge for adoption of the technology is the relatively low capacity factor, ranging from 35.5% in moderate solar areas to 45% in very high solar areas, and in principle reducing the scale of potential applications to approximately 2300MWt across Australia.

Most of the sites in areas of very high insolation are either mining or mineral processing operations located in the vicinity of Newman (WA) or Mount Isa and central Queensland. The potential applications in the moderate solar areas are more diverse, including mining, timber, food and power sites. Unfortunately, most large Australian industrial sites, such as the mining sites, are operated on a continuous basis and would presumably require provision of energy on that basis. The solar plant would therefore require a back-up system and this would make determination of the viability more complex through looking at the combined cost and performance of the two systems.

More detailed case studies were then carried out on sites where electricity generation was in the range of 10-100MWe and heat in the range of 25-250MWt. It was assumed that the plants had up to 6 hours of storage at temperatures up to 750°C for sites representing very high solar to moderate availability. Design and performance modelling of the solar plants at these sites was performed using NREL's System Advisor Model, with subsequent itemised costing and financial performance predictions performed separately. This analysis indicated that the technology is not only affected by the solar availability at the site, but also the scale of implementation. It is likely that the technology is currently only viable on a scale exceeding 100MWe for electricity generation or 250MWt for heat provision. In areas of high to very high solar availability the levelized cost of production of electricity was estimated at $175/MWh and heat production at $14/GJ. While these costs may not currently be attractive in the general market place, some areas of high solar availability in Western Australia, Northern Territory and Central to Western Queensland, where other energy supplies can be limited, may be potential sites for application. This could be improved through increasing the selected 6 hours of storage capacity, but it will always be necessary to provide a back-up source where the industrial applications require continuous and reliable energy supply.

The current cost of the energy to such applications is quite variable, but in most cases this will be based on natural gas for the range of scales best suited to solar thermal applications. For electricity generation this will typically be a simple gas turbine system, but some smaller or more remote applications may also use diesel generators. There will be some influence of scale and location (ie. fuel cost) for the LCOE from these technologies, but Lazard's Levelized Cost of Energy Analysis (2013) indicates that a typical range for utility-scale applications in Australia is US$209-257/MWh for natural gas and US$344-379/MWh for diesel electricity generation. The analysis of the solar thermal technology suggested that an LCOE as low as $175/MWh was possible for larger units, but in the utility scale market (~35MWe) it is more likely to range from $210-280/MWh. Provision of heat from solar thermal technologies is likely to be of similar viability, but requires a more detailed matching with the specific application. This suggests that solar thermal technologies could already be financially viable for some applications, depending on the scale and achievement of a suitable capacity factor, and the 'gap' is perhaps more related to the inability to provide continuous supply and perceptions regarding the technology.

<u>Activity 2</u>

Initial development work was directed at identifying the most appropriate heat transfer and storage media for high temperature solar thermal energy storage applications. This involved a consideration of gases, liquids and solids as potential heat transfer and storage media, including molten salts which can be used as both a heat transfer fluid and a storage medium. The ideal salt formulation should have a low melting point and a high decomposition temperature to facilitate its use as a heat transfer fluid or a thermal energy storage medium. Carbonates were subsequently identified as the most viable option to achieve stability at temperatures of 700°C and above as required for this project. However, the problem with carbonate mixtures that were investigated was that their melting point was around 400°C, which would pose real challenges if they were to be used as a heat transfer fluid. In addition, once a suitable carbonate composition has been identified there will be significant containment issues to be addressed as the carbonates are likely to be quite corrosive with many of the alloys that we might like to use in the absorber and the pipework.

It was ultimately decided that the use of a gas as the heat transfer fluid, where the gas is heated in the absorber/receiver and then subsequently transfers its heat to a solid storage medium, provided the best option within the timescale of this project. Possible gases that were considered in modelling studies included hydrogen, helium, nitrogen, CO_2 and air, with CO_2 (at 6 barg) being selected on the basis of compressor/blower power requirements, heat capacity and heat transfer coefficient. The solid storage options included graphite, silicon carbide or alumina, with high density alumina balls finally being selected as the best compromise between cost and thermal properties.

Activity 3

A schematic of the plant that was built at Newcastle is shown in Figure 1. The critical components of this facility are the 250 kW Receiver/Absorber that is used to heat the CO_2 as it was pumped around the system and the Thermal Energy Storage Vessel that holds the alumina balls into which heat was transferred from the hot CO_2. Operation of this system was based on establishing a stable thermocline in the storage vessel that contained the alumina balls after repeated cycles of charge/discharge.

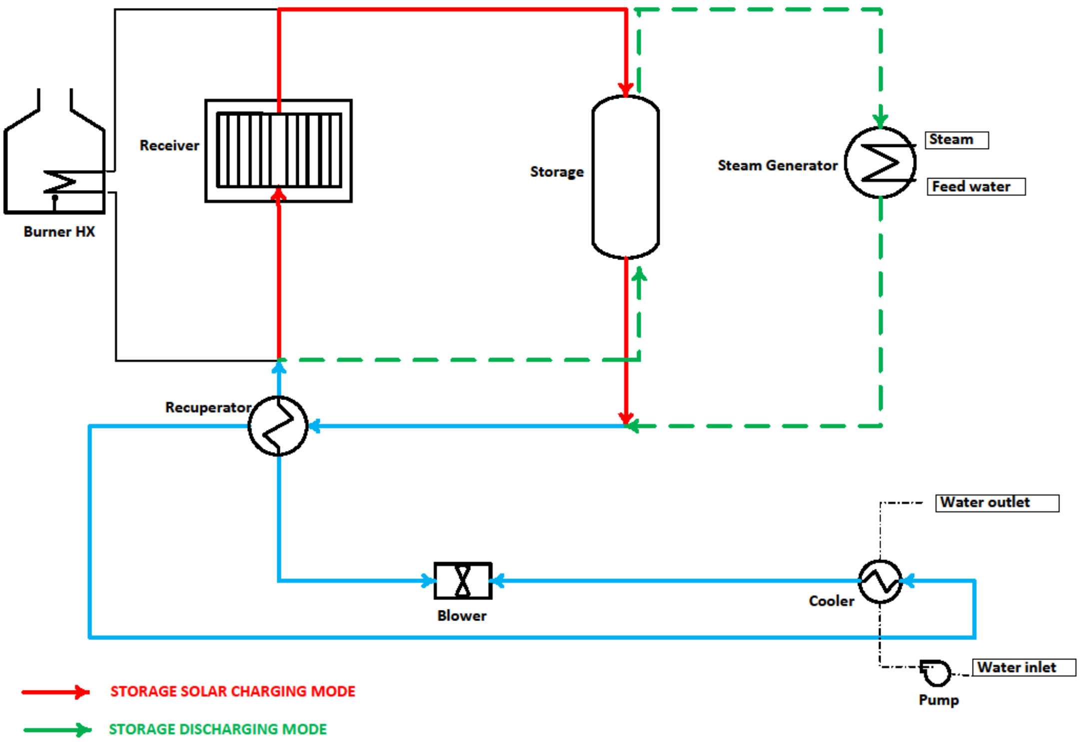

Figure 1 Flowsheet for the thermal energy storage loop

The normal operating scheme for this plant was for the Storage Vessel to be charged with solar energy during the day with the hot gas entering at the top and cold gas leaving at the bottom. This charging would continue until the temperature at the top reached 750°C or the outlet temperature at the bottom reached 300°C. The system would then be operated with CO_2 flowing in the reverse direction so that cold gas entering the bottom was heated during passage through the vessel and then sent to the Steam Generator to raise superheated steam.

Operation of the facility has indeed shown that a combination of CO_2 as the heat transfer fluid and alumina balls as the thermal storage medium is a viable combination for high temperature thermal energy storage. The 20 tonnes of alumina balls that are contained in a 5 metre deep bed appear to be extremely effective at absorbing heat from the hot CO_2 during the charge cycle and transferring is back to the cold gas during the discharge cycle. Pressure drop across the bed has been low thus enabling parasitic energy losses related to pumping the heat transfer gas (CO_2) around the system to be kept to a minimum.

Heat losses, particularly from the top of the Storage Vessel where the bed temperature is at its highest, were so significant that it prevented the system being operated over charge/discharge cycles from one day to the next. Discharge of stored heat from the Storage Vessel via the Steam Generator did, however, prove to be very easy to control with steady generation of superheated steam being achieved.

High temperatures on the outer surface of the top dome of the storage vessel indicated that there were significant heat losses in the top section of the vessel. In spite of this at about 0.5m to 3.0m below the top of the bed, only low thermocline degradation was indicated with bed temperatures dropping by less than 70^{o}C over a 17 hour standby period. Bed temperatures lower in the bed show significant decrease in standby mode. However, this is believed to be due to some level of non-uniform heating across the Storage Vessel in charge mode, as the flow channels through the central region of the vessel towards the centrally located outlet at the bottom of the Storage Vessel. It would appear that the bottom gas distributor which was designed to avoid such a problem is not ensuring an even flow of gas down through the Storage Vessel. This results in cold regions occurring in the bottom of the vessel so that heat is transferred radially by conduction into these regions after shutdown. Large heat losses from some points on the sides of the vessel, as indicated by change in colour of the temperature sensitive paint, have aggravated the non-uniformity in the heating profile in the Storage Vessel.

The Receiver/Absorber had to be constructed from a special high temperature alloy because of the high metal temperatures that arise due to the poor heat transfer that occurs when heating a gas of relatively low density (compared to a liquid heat transfer fluid). In addition CO_2 at high temperatures and pressures can be very corrosive of many metal alloys. It was designed to heat CO_2 from around 250^{o}C as it returns from the bottom of the Storage Vessel to 750^{o}C as it leaves the Solar Receiver. The performance of the Storage Vessel has meant that the temperature of the gas leaving the Storage Vessel was lower than the required 200 to 250^{o}C temperature going into the Receiver/Absorber. This severely limited the performance of the Solar Receiver. The desired inlet temperatures could only be achieved by preheating the gas using the natural gas-fired Heater before it was directed to the Receiver/Absorber to be heated to 750^{o}C. However, indications from our experiments are that provided that the gas can be supplied to the Solar Receiver at its design temperature of around 250^{o}C then it will meet the required duty. Another positive to come out of its performance tests is that the pressures drop across the Solar Receiver/Absorber has been well within design specifications.

Transferability

This project was carried out in collaboration with our industrial partner Abengoa Solar Technology S.A with funding through ARENA. The relationship with Abengoa Solar has been strengthened through this project and new joint projects are underway or in development.

Abengoa Solar is a major world player in solar thermal energy power generation and the learnings coming out of this project will feed directly into future development programs. On-going analysis of the performance of the Thermal Storage Vessel will provide understandings that can be used to benefit in future designs which will avoid some of the problems encountered in this project. Insights from the operation of the Solar Receiver/Absorber will also feed directly into projects where gases are to be heated to high temperatures at elevated pressures. This is particularly relevant to projects such as those incorporating supercritical CO_2 cycles, which are of special interest to both CSIRO and Abengoa Solar.

Conclusion and next steps

In spite of operational limitations of the plant as installed, the project has provided some valuable insights into the challenges involved in storing solar thermal energy at high temperatures.

Thermal energy storage is a key factor in the feasibility of the CSP plants. At high operating temperatures, the best thermal energy storage systems are ceramic regenerative systems. However the cost of the container is usually an impediment in their use at these temperatures.

A new Storage Vessel concept has been built and tested in the project in order to reduce the cost of thermal energy produced. In these tests, hot spots in the top dome of the vessel were observed. Preferential flow channelling was also indicated, affecting the expected thermocline in the bed. These issues along with operational data are now being evaluated for future Improvement of the Storage Vessel design.

The performance of the Solar Receiver/Absorber does indicate that it is capable of performing according to design specifications. The pressure drop across it is not excessive and provided that gas is heated to the design inlet temperature it is capable of producing gas with an outlet temperature of 750^{o}C.

The next steps may well be further development and testing programs (requiring new funding) based on the facility at Newcastle. The Storage Vessel could be modified to improve its insulation and therefore its thermal performance. There may well be some benefit to be gained from using computational fluid dynamics (CFD) to determine flow patterns and heat losses from the Storage Vessel in various configurations, as well as better designs for the flow distributors to provide a more uniform flow.

Further testing of the Solar Receiver/Absorber could be facilitated by modifications to the line between the Gas Heater and the Solar Receiver inlet to enable it to be operated independent of the Storage Vessel. Possible future tests might, for instance, look at the effect of increasing the aperture size on the Solar Receiver to minimise spillage.

Lessons Learnt Report: Design and operation of the thermal energy storage vessel

Project Name: *Development of Advanced Solar Thermal Energy Storage Technologies for Integration with Energy-intensive Industrial Processes and Electricity Generation*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	NSW

Key learning

Alumina balls performed well as a heat absorption and heat storage medium. There was no evidence of them undergoing attrition as a result of the repeated cycles of heating and cooling. The main limitation on the performance of the heat storage unit appears to be thermal insulation. The main problems appear to be on the domed sections at the top and bottom of the vessel. Temperatures in the middle section of the vessel would remain fairly constant. Losses by conduction through inlet and outlet pipework and fittings may also have been a contributing factor. There are also some indications of channelling of gas flow through the bed which may relate to the design of the gas distributors.

Implications for future projects

Clearly a future design of storage vessel would require improvements to the approach used to insulate the vessel. There would of course be some benefits to be had from scale-up of the system as the surface area/volume ratio would be reduced. Some of these issues may best be addressed by some detailed computational fluid dynamics studies that might look at possible causes of the heat losses in our experimental setup and ways of mitigating them in future designs through better choice of insulating materials and improved design of gas distributors.

Knowledge gap

In spite of the fact that the Storage Vessel was heavily instrumented with up to 20 thermocouples inside and outside the vessel, the size of the vessel meant that there are many uncertainties about the temperature distribution inside the vessel and the flow path of gases through the packed bed of alumina balls.

Background

Objectives or project requirements

The *Advanced Solar Thermal Energy Storage* project sought to identify suitable combinations of heat transfer fluid and heat storage medium that could store solar thermal energy at up to 750^{o}C.

Process undertaken

A test facility was built at the CSIRO Energy Centre in Newcastle, NSW, to provide for the storage of 750 kWh of solar thermal energy in alumina balls using CO_2 as the heat transfer fluid. The heat was collected by a purpose-built receiver, mounted on a 25 m high tower that was illuminated by a heliostat field, with the high pressure CO_2 being pumped around the test loop and through the Thermal Storage Vessel by a high pressure Blower.

Lessons Learnt Report: Use of molten salts for high temperature applications

Project Name: *Development of Advanced Solar Thermal Energy Storage Technologies for Integration with Energy-intensive Industrial Processes and Electricity Generation*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	NSW

Key learning

The investigations carried out into molten salts within this project clearly indicated that modifications to conventional nitrates could not provide acceptable levels of stability at temperatures above 600°C. Even use of tertiary/quaternary systems, involving the addition of various cations and anions to sodium/potassium nitrates failed to solve problem. Carbonates seem the best option for achieving stability at high temperatures but it was found to be difficult to get their melting point much below 400°C, even with the addition of wide range of additives. Materials containment problems are likely to be a major issue even if a suitable composition can be found. These salts are likely to be very corrosive of any metal with which they come in contact.

Implications for future projects

While the use of molten salts as a heat transfer fluid and storage medium has many attractions, chiefly the ability to use a two tank system and the stable heat transfer conditions such systems offer, much more development work is required on molten salt systems and materials to contain them before they will be viable at temperatures beyond those which can be achieved with sodium/potassium nitrate systems.

Knowledge gap

The key knowledge gaps are molten salt compositions that have high temperature stability but low melting points, as well as suitable materials to contain them.

Background

Objectives or project requirements

The *Advanced Solar Thermal Energy Storage* project sought to identify suitable combinations of heat transfer fluid and heat storage medium that could store solar thermal energy at up to 750°C, including a significant effort that was devoted to developing suitable molten salts.

Process undertaken

Laboratory scale test facilities at the CSIRO Energy Centre in Newcastle, NSW, and the CSIRO Clayton site in Victoria were used to develop a wide range of salt compositions and then test their thermal properties using techniques such as Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC).

Lessons Learnt Report: Mechanical design and construction of systems for handling gases at high temperatures and pressures with thermal cycling

Project Name: *Development of Advanced Solar Thermal Energy Storage Technologies for Integration with Energy-intensive Industrial Processes and Electricity Generation*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar Thermal
State/Territory:	NSW

Key learning

Generally process plants are designed to operate for extended periods under conditions that approach steady state. The unsteady state conditions inherent in solar based systems where there can be large variation in insolation throughout the day, together with the regular cycling temperatures associated with charge/discharge cycles used in this project, pose great limitations on the mechanical design of pipework and vessels. Developing a design which allows for expansion/contraction with change in temperature has been a major challenge in this project, requiring extensive finite element analysis studies to develop solutions to the problems that arose. Chief among these were the long runs of piping between the Receiver at the top of the Tower and the Storage Vessel at ground level. Supports had to be developed that would allow for considerable expansion of very hot pipes without these supports becoming a heat sink that would result in loss of heat from system. There was also a need to avoid flanged joints which meant all connections had to be welded and subsequently X-rayed, increasing the cost of the installation. The complexity of the installation posed a real challenge for Australian fabricators who were faced with having to work with special alloys, develop new weld procedures and achieve high levels of precision. Even sourcing fittings, such as the high temperature valves used to direct the flows, proved to be a difficult and time consuming exercise.

Implications for future projects

In planning future projects greater allowance needs to be made for the time and costs involved in sourcing and developing the knowledge and skills to overcoming some of the design problems associated with projects that are at the cutting edge of technology. Research where new knowledge and understanding are required cannot always be done to the same strict timetable as many other projects that apply existing knowledge.

Knowledge gap

Much has been learnt during the course of this project by both the scientists and engineers involved, both within CSIRO and Australian industry, that could be put to good use in any future project. There is still much more work to be done on material development for systems operating in the high temperature environment characteristic of solar thermal systems.

Objectives or project requirements

The *Advanced Solar Thermal Energy Storage* project sought to demonstrate proof-of-concept of the integration of a solar thermal storage system with a solar energy concentrator/receiver facility to store high grade heat that, at a subsequent commercial scale, could be used on demand by electricity generators and other industrial processes

Process undertaken

A test facility was built at the CSIRO Energy Centre in Newcastle, NSW, to provide for the storage of 750 kWh of solar thermal energy in alumina balls using CO_2 as the heat transfer fluid. The heat was collected by a purpose-built receiver, mounted on a 25 m high tower that was illuminated by a heliostat field, with the high pressure CO_2 being pumped around the test loop and through the heat storage vessel by a high pressure Blower.