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Experiences From Using Molten Sodium Metal As A Heat Transfer Fluid In Concentrating Solar Thermal Power Systems

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Abstract

Molten sodium metal is receiving increasing interest worldwide as a candidate for the heat transfer fluid in central receiver solar thermal plants. Sodium exhibits superior thermal conductivity properties and coupled with a suitable working temperature range, it permits high flux intensities and receiver efficiency.

Management of the reactive nature of the alkali metal requires careful design and implementation. Vast Solar has 5 years of experience working with sodium at their 1.2MWth demonstration and testing facility. During this time Vast Solar has developed a suite of safety and emergency response procedures related to sodium that have all been incorporated into the 6MWth Pilot project.

Earlier this year, the safety procedures were put to practical test during commissioning of the 'cold' sodium tank at the 6MWth Pilot plant. Learnings from the response including liaison with Emergency Services are presented in this work. The successful incident response has reaffirmed Vast Solar's continuing leadership in the application of sodium as a heat transfer fluid to concentrated solar thermal power.

1. Introduction

Vast Solar is developing a Concentrating Solar Power (CSP) technology for power generation application at utility scale. Vast Solar employs a low-cost and modular model for capturing solar thermal energy with multiple solar array fields and receivers.

Central receiver solar thermal power plants require an efficient method to capture, transport and store heat. Sodium is a leading candidate heat transfer fluid (HTF) and is utilised in Vast Solar's current 1.1MWe projects and proposed 30MWe project.

1.1. Molten Sodium as a Heat Transfer Fluid

Sodium has significant advantages over other industry standard heat transfer fluids such as solar salt and thermal oil. Superior thermal conductivity, a wide working temperature range, low freezing point and low vapour pressure make it particularly suitable for the high efficiency modular fields and receivers used by Vast Solar (Boerema et al., 2012).

Sodium requires careful management due to its highly reactive nature. In most cases sodium will burn on contact with air and react violently with water. Vast Solar has put in place a variety of design philosophies, safety procedures and management systems to help reduce the risks associated with the use of sodium in its plants.

1.2. Jemalong Solar Station

Jemalong Solar Station (JSS) is a research and demonstration facility designed to provide the final testing of Vast Solar's various technology before building its first commercial scale plant (planned 30MW JSS1). The JSS includes 5 solar arrays each of 699 heliostats and 5 corresponding tower mounted receivers.

Sodium is pumped from the HTF Cold Storage Tank (Cold Tank) at 270°C to the receivers where the sodium is heated in the receiver to 560°C. The high temperature sodium returns via the pipe network to the HTF Hot Storage Tank (Hot Tank) where the thermal energy is stored. The stored heat is then used to generate steam and produce electrical power through a conventional Rankine cycle turbine. All power generated by JSS will be exported to the electricity network. The JSS project is approaching mechanical completion and will soon move into commissioning phase.

2. Sodium Leak and Fire

On Saturday 13th of June 2015 a small sodium leak occurred in the HTF circuit. The sodium was at a temperature of 105°C and it ignited on contact with the air. The leak rate was estimated at approximately 1L/min.

Over the ensuing hours the leak resulted in a burning pool of sodium roughly 2.5m in diameter. The situation was complicated by the fire burning below the 'Cold' tank.

Figure 1. Sodium Fire at approximately 40 minutes after it was first reported.

2.1. Emergency management during the incident

Emergency management procedures for the JSS were correctly followed by employees on site at the time of the incident. The initial response called for the evacuation of the site and calling emergency services.

With no danger to surrounding property or personnel, emergency services monitored the situation while gathering all necessary information and resources.

Vast Solar had previously briefed the local emergency services on the appropriate response and methods to manage sodium fires, however the rare nature of sodium fires and the significant scale (~1000kg) called for an appropriately cautious response. Over the next 7 hours resources and plans were developed to extinguish the fire with Hazmat specialists flying into the site.

Prior to the incident, Vast Solar's practical experience was limited to handling small scale sodium fires (<1kg) and there was very little experience with sodium fires amongst the emergency response specialists.

Initially, firefighting efforts made use of light soda ash (Na_2CO_3) propelled by portable fire extinguishers, see Figure 2. This proved ineffective for the scale of the sodium pool and fire.

A 1200kg quantity of soda ash was stored on site in 20kg bags. Several bags were spread over the edge of the pool which proved to be highly effective in retarding the fire. It was clear that 1200kg of soda ash would not be sufficient and so resources were scrambled to find additional soda ash.

Figure 2. Fire fighters in breathing apparatus during a firefighting operation.

At around 5pm the emergency services crew decided to extinguish the fire with the available bulk soda ash. The fire was quickly extinguished over the next 15 minutes. While there was insufficient soda ash to completely encase the sodium pool, the soda ash extinguished 99% of the fire.

The fire was always fully contained and there was never any risk of injury, however its difficult position and the length of time the fire was allowed to burn (nearly 8 hours) greatly amplified the scale of damage and the publicity it attracted.

Additional soda ash was sourced from surrounding towns and cities however the majority did not arrive until Sunday morning. This was used to create a soda ash mound over the sodium effectively entombing the sodium pool.

The temperature within the sodium mound was monitored over the next week at 2 hour intervals. Heavy rain flooded most of the site 2 days after the fire. Precautionary measures were enacted and while some water was able to get onto the soda ash mound there were no significant flare ups.

2.2. Observations of the sodium fire

The sodium fire burned with a warm yellow coloured flame as seen in Figure 1. The fire produced a large volume of a dense white smoke. When sodium burns in air sodium oxides are produced which is form some of the smoke constituents. The oxides are carried away in the smoke plume rapidly decompose. Measurements of the pH of the smoke were taken by the HazMat crew, who found that at a distance of 40m the smoke had a neutral pH.

Very little free hydrogen is produced by a sodium fire so there is no risk of a large hydrogen detonation.

The EPA took soil samples from around the site, away from the fire location and found that no contamination was spread from the smoke plume. These observations are consistent with previous literature on sodium fires (Luster. and Freudenstein, 1996 and Olivier et al, 2007).

Once the fire was under control, the firefighting crew used a thermal imaging camera to measure and monitor the temperature of the soda ash mound. Readings of greater than 700°C were observed in the hot spots.

A metallurgical investigation of the Cold Tank demonstrated that the steel did not undergo any significant strength or microstructural changes as a result of the fire below and therefore the tank remains fit for service. The lack of sensitisation of the austenitic stainless steel indicates that the steel did not get heated above 500°C for any extended period of time. It is postulated that the high thermal conductivity of the sodium in the tank was effective at transporting the heat away from the tank surface and into the bulk of the sodium inside the tank.

The cold tank was supported on either end by two concrete plinths with a tie beam connecting the plinths. The tie beam was lifted over 1m out of the ground causing the tank to be lifted approximately 100mm. The heat of the fire had baked the clay under the tie beam which expanded and buckled the beam.

2.3. Ongoing cooperation with Emergency Services

Due to the unusual nature of this fire, significant interest was generated within the Fire Department. HazMat specialists from all over the state and Queensland visited the site, in addition to senior officers of the NSW Fire Department, who visited via helicopter on the day of the fire. This interest has been extremely beneficial for Vast Solar as the Fire Brigade is putting together a case study of the incident. Feedback from all emergency services was overwhelmingly positive with praise given on the high degree of prior consultation and communication during the incident. Vast Solar and the NSW Fire Department will continue to collaborate in order to facilitate training and to further develop understanding of sodium fires and the most effective extinguishing measures.

3. Incident investigation

Vast Solar has conducted a complete internal investigation into the incident. The investigation included a review of procedures, root cause analysis of the incident and a design review of the HTF system in light of the incident. Implementing the findings of this investigation is currently underway during the rebuild of the affected areas of the site.

Vast Solar has learnt many lessons from this incident, the majority of which will be made public. Outlined below are the key learnings identified by Vast Solar not related to our IP;

3.1. Lessons Learnt

A much greater understanding of sodium fires has been gained through fighting this fire, especially fires of the scale encountered in this incident.

The learnings are summarised as follows:

1. Sodium fires can be safely and quickly extinguished with Soda Ash. Bagged soda ash is highly effective. It is an excellent retardant and can be used to completely smother the fire if enough soda ash is available.
2. Soda ash is best applied by manually shovelling or dumped via a bucket from a Telehandler or tractor directly onto the sodium fire. A small covering of soda ash is extremely effective at extinguishing sodium.
3. Soda Ash is relatively cheap and a large quantity should be available on site. Vast Solar has determined that 20 tonnes is appropriate for its pilot facility with 120 tonnes of Sodium.
4. Water treatment plants are major users of soda ash and can be called upon in the event of emergencies to supply significant quantities.
5. The dense white smoke from a sodium fire is non-toxic and doesn't cause contamination to surrounding farm land. The EPA tested soil samples around the site and also in the direction of the smoke plume and found no contamination. The fire services HazMat team tested the smoke plume at a distance of 40m from the fire and found it to have a neutral pH.
6. Sodium smoke is very thick and dense and is a mild irritant. It rises rapidly away from the fire and its clear visibility makes it very easy to avoid when approaching the fire.
7. Exposure to sodium smoke is irritating but this irritation is similar in severity to exposure to the smoke from a wood fire.
8. Sodium fires generate a very large amount of smoke. Under no circumstances should the HTF circuit be within a confined space as the smoke would rapidly fill the space making firefighting impossible.
9. Class D fire extinguishers are of little value when dealing with a reasonable size fire. For very small leaks (<1kg) they may be effective but the best option would still be bagged soda ash. Having fire extinguishers available may result only in delaying the use of the safest and most effective tool available in bagged soda ash.

10. The large special purpose Class D fire extinguisher was awkward to use and is not recommended. It is difficult and heavy to manoeuvre. It is necessary to get very close to the fire before deploying. It is far easier and more effective to carry bags of soda ash to the fire and shovel or put the bag directly onto the fire.
11. Once the sodium is covered with soda ash it doesn’t flare up and little or no smoke is observed. A thin cover of soda ash effectively suppresses the fire and smoke.
12. If sodium leaks from beneath the soda ash it often does not ignite which may be due to its mixing with soda ash. It glows for a time while a cover forms which appears to quench the reaction.
13. The waste from a sodium fire is easily dealt with.

4. Conclusion

The sodium leak and fire at the JSS site has demonstrated the effectiveness of the emergency response procedures put in place Vast Solar. The unusual nature of the sodium fire and challenging location of the leak has highlighted improvements to be made to system design and incident response. These improvements are in process of being incorporated into current and future Vast Solar projects.

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