

# Molten Salts and Applications I: Molten Salt History, Types, Thermodynamic and Physical Properties, and Cost

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**Abstract:** Excess energy from solar, nuclear or coal power stations can be stored in molten salts (MS) in the 565 °C range. At elevated temperature, large containers can be used to store energy for up to a week and generate eight hours or more, depending on the container size, of electricity to be used at night or during peak demand hours. A stable diurnal energy supply is made available by energy storage and the fluctuation experienced at thermal solar power stations caused by weather conditions is reduced. Supported by Office of Naval Research (ONR), this paper presents a survey of molten salt properties used in solar power storage, as well as the history of molten salt usage for energy storage and production. The history of molten salt usage includes past, current, and future developments involving molten salt usage for nuclear and solar energy storage and production. Density, melting temperature, viscosity, electric conductivity, surface tension, and heat capacity of various molten salts are discussed. Since costs are important factor in selecting a molten salt compound, salts costs are presented. Recommendations are made regarding the efficient use of various types of molten salt.

**Key words:** Molten salt history, molten salt technology, molten salt properties, molt salt costs, solar energy storage, nuclear energy storage.

## 1. Introduction

Molten solar salts are effective at storing excess energy because they have considerable capacities for heat storage. Large insulated tanks provide a closed system for these molten salts to be properly contained. This paper examines the various molten salts available for MS storage, including their physical and thermodynamic properties, and corrosion properties. In addition, the history of molten salts and the usage in nuclear and solar energy is discussed. The material presented in this paper has been collected by the researchers in the University of Nevada, Las Vegas (UNLV) Molten Salt Project and information provided by Dr. Craig Tyner in a report to the project [1, 2].

This is the first paper of a series on Molten Salt Research, followed by “565 °C Molten Salt Solar

Energy Storage Design, Corrosion, and Insulation” [3] and “Worldwide Molten Salt Technology Developments in Energy Production and Storage” [4].

## 2. A History of Molten Salts

The first use of molten salts dates back to 1950, which is when Oak Ridge National Laboratory (ORNL) started to develop and test a nuclear powered aircraft engine using molten salts. In 1954, ORNL shifted their molten salt focus to nuclear reactors. The thermal stability of molten salts was of great interest in the development of these nuclear reactors since they would not decompose when exposed to the high temperatures associated with nuclear reactors. The U.S. Atomic Energy Commission (AEC) was interested in studying various breeding reactor concepts. A relatively successful molten salt test breeding reactor was developed in the 1960s at ORNL. However, during this time, the Molten Salt Reactor Experiment (MSRE) was directly competing with another nuclear reactor project,

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which was the Liquid Metal Fast Breeding Reactor (LMFBR) project. During the 1960s, the LMFBR project pursued an aggressive funding campaign to develop its reactor. After the MSRE was successfully completed in 1969, ORNL wanted to pursue additional funding from the AEC. When the MSRE was ready to pursue \$350 million of total funding in the 1970s, the AEC was committing \$400 million per year through 1975 on the LMFBR project, and the AEC did not want a competing project. This ultimately led to the end of molten salt nuclear reactor research in the United States, as ORNL published its last report on the MSRE to the AEC in 1976. The final reactor from the MSRE was a demonstration breeding reactor that addressed both the tellurium induced cracking in the reactor as well as the interactions involving tritium and the reactor coolant. Finally, once the MSRE had been terminated at ORNL, societal changes doomed the molten salt nuclear reactor, particularly the avoidance of a uranium shortage that meant that molten salt reactors were not in high demand, as well as fears of uranium proliferation and reactor accidents. However, in 1980, ORNL did publish one last report on a conceptual design for new type of breeding molten salt reactor using denatured uranium, but the design never came to fruition [5-7].

The first molten salt reactor built by ORNL was completed in 1954 and operated for several days, operating a maximum temperature of 1,620 °F. The early molten salt reactor concepts were non-breeding reactors using various molten fluorides, including uranium fluoride (UF<sub>4</sub>) and thorium fluoride (ThF<sub>4</sub>) [8]. However, by 1959, all interest in molten salt reactors from the AEC was solely with breeding reactor concepts. As such, the MSRE was proposed to the AEC in order to develop and test a molten salt breeding reactor [6] (A breeding reactor is a reactor that produces more fissionable material than it consumes). The breeder reactor, which was designed to produce 10 MW of electricity, started construction in 1962 and was made operational in 1965. The MSRE, along with the

LMFBR project, were both included in the 1962 "Report to the President" for President John F. Kennedy, a report that promoted the benefits of breeding reactor research. It was after this report that the LMFBR pursued its aggressive funding campaign. While the MSRE project was considered a success, there were some concerns that needed to be addressed, including three major concerns. The first concern was that the Hastelloy-N being used in the reactors was subject to radiation hardening in which helium was accumulating at grain boundaries due to carbide precipitates in the alloys. The second concern was when the tritium, which is radioactive hydrogen, was produced by neutron reaction with lithium. This is a concern because the tritium can penetrate various metals. The final concern was the development of small cracks in Hastelloy-N piping due to tellurium. Ultimately, the solutions to these issues were addressed [9, 10]. To prevent the radiation hardening, it was recommended that fast neutron radiation be limited around vessel walls. For the excess tritium production, it was discovered that a salt coolant could absorb the tritium, and that the coolant could further be removed, which would allow for the purging of tritium. As for the tellurium cracks, research showed that cracking could be limited if the fuel was kept on the reducing side of the reactor. Despite finding the solutions to these issues, which lead the research team at ORNL to believe the project was ready for the next step once the original MSRE was completed, it found itself competing with the LMFBR project for funding, which was further along and heavily invested in than the MSRE. In addition, the AEC wanted industrial support for the MSRE research. Industrial support was available for the molten salt reactors, but the AEC ignored this support and eventually ordered the research be ceased. This was also despite the fact that it was expected that the capital cost of the molten salt reactors was less than the LMFBR [9, 10]. This was because of the fact that the fuel handling is simpler, molten salts have a higher heat capacity than sodium,

molten salt reactors do not have to worry about a “core disruptive accident” happening, molten salts have a smaller thermal conductivity to limit thermal shock, and the coolant is more compatible with water [5]. For energy storage uses, this shows that molten salts are useful because of their thermal capacity and conductivity, as well as being relatively safe, even in a nuclear reactor environment.

The first solar power plant that used molten salts for energy storage was developed in 1993. Solar Two, located in the Mojave Desert in California, was designed a test facility for molten salt energy storage (MSES). This facility was designed to store 10 MW of electricity for one hour. As a concentrating solar power (CSP) facility, various reflective panels, or heliostats, were used to reflect sunlight into centralized tower. These towers would absorb the reflected sunlight and use the energy as heat, which would then heat the molten salt and therefore store the energy in the salts as heat. While Solar Two provided valuable insight into use of both MSES and CSP, the maintenance had become exhaustive and the facility was not being maintained properly, which was undercutting the performance of the system. Ultimately, Solar Two was decommissioned in 1999. Afterwards, the NREL published a short report in 2000 on their findings, while Sandia National Laboratory published its detailed report in 2002, documenting the full research provided by this project [11, 12]. This information has proven valuable to the commercial development of MSES worldwide as widespread efforts are made to introduce MSES to the world.

### **3. Molten Salt Usage**

The biggest feature of molten salts is their ability to conduct heat. This is the defining characteristic for molten salt technology in both molten salt reactors (MSR) and molten salt energy storage systems (MS-ESS). They can also be used to conduct electricity, which is useful in decomposing molten salts [13].

As stated earlier, molten salts were first used to

develop nuclear reactors. These reactors use molten salt fuels, usually fluoride mixed with any of the following: thorium, uranium, lithium and beryllium. This contrasts with the solid fuel used in traditional nuclear reactors. MSRs are known for their unrivaled safety when compared to various other types of reactors. Compared to other nuclear reactors, molten salt nuclear reactors cannot melt down because the fuel is already molten to start with. A safety feature of molten salt nuclear reactors is that if the resulting fission produces overheating in the reactor, which would be over 700 °C, the fuel will spill out of the reactor, usually by melting a spill plug, into a circulation loop filled with water. This in turn decreases the fission in the tank, and as a result, the tank cools down. In addition, in the event of a tank breach, the fuel will simply freeze at atmospheric temperatures. Also, since the fuel is not pressurized like traditional reactors, radiation will not disperse into the atmosphere during a breach. Molten salt nuclear reactors also produce less nuclear waste than traditional reactors. In traditional reactors, the fission produced by the uranium rods creates xenon, which can crack the ceramic rods. Once the rod is cracked, it must be disposed of even if there still is usable fuel. With molten salt reactors, the fuel is in liquid form and therefore does not use ceramic rods. As for the gas that is produced in molten salt reactors during fission, it simply rises to the top of the tank where it can be captured and removed. Because of its inherent safety, molten salt nuclear reactors are cheaper than traditional reactors because molten salt reactors require fewer safety measures and less redundancy than traditional reactors. Lastly, molten salt reactors can limit nuclear weapons proliferation because most of the actual fuel, which are the actinides, is consumed by the actual reactor, reducing the amount of waste available for proliferation. Also, the reactor can use the nuclear waste from traditional reactors as fuel, which can reduce the waste that is available for proliferation [14].

One of the biggest benefits of molten salt nuclear

reactors, as well as molten salt energy storage systems, is that they do not emit carbon like coal and natural gas power plants. Some molten salt nuclear reactor concepts, such as the liquid fluoride thorium reactor (LFTR), can consume 99% of its fuel. Whatever waste products that are produced only have to be buried for only 300 years compared to the minimum of 10,000 years for most traditional reactors. LFTRs can be made to be smaller than traditional reactors, allowing for a wider range of applications. Also, since LFTRs operate at higher temperatures than traditional reactors, LFTRs can take advantage of more efficient conversion cycles in converting heat into electricity [15, 16].

The most unique feature of molten salts compared to other reactors is that they serve as both the fuel and coolant for the reactor. In addition, molten salts are chemically inert, meaning that neither air nor water will cause them to combust. The operating temperature of the molten salt reactor (973 K) is significantly less than the melting point of the molten salts, which is at least 1,670 K. The only concern for molten salt nuclear reactors is that there has not been any recent accident analysis performed on these reactor concepts to provide insights into what a molten salt reactor accident would resemble. This can pose challenges to regulators in trying to assess the full risk of molten salt reactors. However, as stated earlier, molten salts are self-containing in the event of an incident or accident [16].

These considerations could help reverse a trend where not only nuclear reactor development in the United States is coming to halt, but some current reactors are being decommissioned [17]. However, as the United States is weary of nuclear reactor development, other countries are exploring MSR development, which includes China, Canada, and the Netherlands [18-21].

The Chinese central government is financing the development of two molten salt nuclear reactors in northern China to help supply China's electrical demands. The reactors are expected to be running by 2020 with the main fuel for these reactors being

thorium based salts. The main reason for this is because of China's abundance of thorium. However, these molten salt nuclear reactors will also be able to consume existing uranium based salts. The main challenge affecting the development of these reactors is the effects of the molten salts on the piping used for the reactors. Successful implementation of the reactors could lead to the development of molten salt nuclear reactors for military uses. Molten salt nuclear powered drones and reactors on Chinese naval ships and aircraft carriers are being considered [18, 19].

Canadian regulators are currently assessing an MSR design by Terrestrial Energy, Inc. (TEI). TEI is developing a project called the Integral Molten Salt Reactor (IMSR). The IMSR uses molten uranium salts to both cool the reactor and serve as the fuel in the reactor. Cooling is achieved through heat decay, in which heat is transferred through the natural convection in the tank, and then simply absorbed by the tank walls. If this concept passes regulatory inspection, the next step is to locate a site in which to construct the project, which includes the Canadian National Laboratory in Chalk River, Ontario. The development of a similar concept has been invited by the U.S. Department of Energy (DOE) to their loan guarantee program, which promises that the DOE will finance the construction of the project at the Idaho National Laboratory (INL) [20].

In The Netherlands, the world's first thorium based MSR experiment in 40 years is being undertaken at Nuclear Research & Consulting Group (NRG). This reactor concept will use a compound composed of thorium fluoride and lithium fluoride salts placed in four crucibles to produce power. If successful, a second reactor concept using a beryllium fluoride and lithium fluoride compound will be tested [21].

In addition to MSR, the development of Molten Salt Energy Storage Systems (MS-ESS) has accelerated worldwide [13]. After the development of Solar Two in 1993, MS-ESS technology has evolved, as there are currently 44 MS-ESS plants either operational or under

**Table 1 Major physical properties of solar salts at melting point [22-24].**

Compound or mixture	Melting point (°C)	Density (g/cm <sup>3</sup> )	Viscosity (mPa·s)
Sodium nitrate—NaNO <sub>3</sub>	306.5	1.900	3.038
Lithium nitrate—LiNO <sub>3</sub>	253.0	1.781	7.469
Potassium nitrate—KNO <sub>3</sub>	334.0	1.865	2.965
Sodium chloride—NaCl	800.7	1.556	1.459
Solar salt (60:40 Na:K nitrate by weight)	225 (approximate)	1.870 (at 625 K)	3.172*

Values with a single asterisk (\*) have been extrapolated for the Solar Salt mix at 580 K.

construction, as well as 24 more plants in the planning stages. This development is further discussed in “Worldwide Molten Salt Technology Developments in Energy Production and Storage” [4].

#### 4. Types of Molten Salts

Of the various kinds of salts that can be melted for use as a molten salt, this report will mostly focus on five salts: sodium nitrate, lithium nitrate, potassium nitrate, sodium chloride, and a mixture of 60% sodium nitrate and 40% potassium nitrate (by weight), commonly called solar salt. These salts have been most prominently mentioned in the literature and are being used molten salt storage facilities since they are cost effective [22]. Based on Janz (1967), calcium nitrate, potassium chloride, and lithium chloride are other salts that can be used in these applications, both alone and in mixture form [22].

#### 5. Physical Properties of Molten Salts

In determining a proper molten salt compound, physical properties, including melting point, density, viscosity, and heat capacity, must be considered. The loading on the storage tanks and pipes can be affected by the density of these solar salts. An approximation of the temperatures these storage tanks will experience is derived from the melting temperatures of the salts. This can be used to determine ultimate strength, thermal expansion, heat shielding requirements, and thickness of the tanks. The resistance of the molten salt while flowing through the pipes is the viscosity. The measure of force a liquid exerts on a surface by interacting with the surface is the surface tension of the molten salt. In

addition, the salt’s ability to conduct electricity is its electrical conductance. The melting points of these various salts, as well as their densities and viscosities at melting point, are shown in Table 1.

Amongst the presented molten salts, the lowest density salt presented is sodium chloride with a density of 1.556 g/cm<sup>3</sup> [23]. The next lowest density salt presented is lithium nitrate with a density of 1.781 g/cm<sup>3</sup> [23]. Lastly, the highest density salt presented is sodium nitrate with a density of 1.900 g/cm<sup>3</sup> [23]. Density, when compared to melting point, is not as important of a consideration because of the small relative difference in densities between these salts.

The solar salt mixture has the lowest melting point presented with an approximate melting point of 225 °C [24]. Lithium nitrate has the next lowest melting point at 253 °C [23]. The highest melting salt presented is sodium chloride at 800.7 °C [23]. With the melting point of a salt being an important consideration for molten salt applications, the best salt presented based on this criterion is the solar salt mixture since it has the lowest melting point considered. Likewise, sodium chloride with the highest melting point considered is the worst salt presented.

The least viscous salt presented is sodium chloride with 1.459 mPa·s [22]. The next least viscous salt is potassium nitrate with 2.965 mPa·s [22]. Lastly, the most viscous salt presented is lithium nitrate with 7.469 mPa·s [22]. Viscosity is not the most important molten salt consideration. However, viscosity does detail the expected resistance from each molten salt while flowing through the piping, which can be an important design consideration of a molten salt system.

**Table 2** Minor physical properties of solar salts at melting point [22, 24].

Compound or mixture	Surface tension (mN/m)	Electrical conductance (S/cm)
Sodium nitrate—NaNO <sub>3</sub>	116.35	0.9713
Lithium nitrate—LiNO <sub>3</sub>	115.51	0.3958
Potassium nitrate—KNO <sub>3</sub>	109.63	0.6324
Sodium chloride—NaCl	116.36	0.8709
Solar salt (60:40 Na:K nitrate by weight)	121.80 (at 510 K)	0.7448*

Values with a single asterisk (\*) have been extrapolated for the Solar Salt mix at 580 K.

**Table 3** Thermodynamic properties of solar salts [22, 25-28].

Compound or mixture	Specific heat capacity (J/mol/K)	Thermal conductivity (kW/mol/K)	Heat of fusion (kJ/mol)
Sodium nitrate—NaNO <sub>3</sub>	131.8	5.66	15.50
Lithium nitrate—LiNO <sub>3</sub>	99.6	5.82	26.70
Potassium nitrate—KNO <sub>3</sub>	115.9	4.31	9.60
Sodium chloride—NaCl	48.5	8.80	28.16
Solar salt (60:40 Na:K nitrate by weight)	167.4 (at 510 K)	3.80	13.77

Since some values were given in calories in some sources, they were converted into joules for this table (1 cal = 4.184 J or 1 kcal = 4.184 kJ) [28].

However, a cold salt temperature of about 285 °C is generally specified to allow adequate margin to prevent salt freezing. The relatively high melting point of solar salt requires that all piping (except exposed receiver tubes, which must be drained when not operating) be carefully insulated and heat traced. Note that power towers are typically designed with the receiver and steam generator higher than the MS tanks, such that the system can be fully drained back to the tanks on an overnight basis. While the 240 °C freezing point of solar salt requires significant efforts in heat trace throughout a plant, this is workable with only minor impacts on cost. The freezing point also must be well below the lower working limit of the power cycle. Typical tower and trough systems use a reheat Rankine steam cycle with a low-side temperature of about 285 °C. If the system used another power cycle (e.g., Brayton) with higher upper and lower temperature limits, a higher freezing point might be acceptable (subject to heat trace and materials compatibility difficulties, of course).

Information of the surface tension and the electrical conductance of these molten salts are presented in Table 2. Despite not being highly relevant in the selection of molten salts, these properties are included

because there are some important design considerations associated with these properties.

The salt with the lowest surface tension presented is potassium nitrate with 109.63 mN/m and the next lowest salt is lithium nitrate with 115.51 mN/m [22]. In addition, the salt with the highest surface tension is the solar salt mixture with 121.80 mN/m [24]. Surface tension is not an important consideration in selecting a molten salt, but it does measure the force exerted by the flowing molten salt in the pipes, on the pipe surfaces, which also affects the pumping loads required to move the salt in the pipes. Since most pipes are flooded, this information may not apply in those cases. However, if the molten salt system is subject to a seismic event, the surface tension affects the wave motion and sloshing inside the tanks and pipes.

The highest electrically conductive salt presented is sodium nitrate with 0.9713 S/cm [22]. The next highest conductive salt presented is sodium chloride with 0.8709 S/cm [22]. Lastly, the lowest electrically conductive is lithium nitrate with 0.3958 S/cm [22]. Electrical conductance is a minor consideration for solar salts in energy storage applications compared to other considerations [13]. This information can be useful if a magnetic flow meter is used to measure the

flow of molten salts through piping. This is because magnetic flow meters require the fluid to be electrically conductive in order for its flow to be detected by the flow meter.

## **6. Thermodynamic Properties of Molten Salts**

Thermal properties can impact application choices as well, although generally to a lesser extent. Nitrates seem to have a heat capacity of around 1,500 J/kg-K, so the details of nitrate selection do not depend significantly on heat capacity.

There are chloride-based salts that have a heat capacity of about half that of nitrates, so costs could be higher using chlorides than nitrates to achieve higher temperatures. An important design factor is thermal conductivity which significantly impacts receiver and steam generator design. In this regard, nitrates (about 0.5 W/m-K) are not really very good thermal conductors, and if compared to liquid sodium, their conductivity is two orders of magnitude lower. However, liquid sodium is definitely not safe for thermal energy storage [2].

The main purpose of solar salts is to store heat for long periods of time. The required amount of heat needed to convert a substance from a solid state to a liquid state is the heat of fusion, its ability to store heat is the specific heat capacity of that substance, and its ability to conduct heat through said substance is the thermal conductivity of that substance. All of these properties are important since these properties detail how the salts conduct and store heat. The thermodynamic properties of solar salts are compared in Table 3.

The solar salt mixture has the highest specific heat capacity presented with 167.4 J/mol/K [27]. The next highest capacity salt is sodium nitrate with 131.8 J/mol/K [22]. In addition, the lowest capacity salt is sodium chloride with 48.5 J/mol/K [22]. The best salt to use for energy storage based on this consideration is the 60% NaNO<sub>3</sub> + 40% KNO<sub>3</sub> mixture because it has the highest heat capacity. Meanwhile, the least

effective salt presented is sodium chloride because it has the lowest heat capacity.

Sodium chloride has the highest thermal conductivity with 8.80 kW/mol/K [25]. Lithium nitrate has the next highest conductivity with 5.82 kW/mol/K [25]. Lastly, the solar salt mixture is the least conductive with 3.80 kW/mol/K [25].

Potassium nitrate has the lowest heat of fusion with 9.60 kJ/mol [26]. The solar salt mixture is the next lowest with 13.77 kJ/mol [27]. Sodium chloride has the highest heat of fusion with 28.16 kJ/mol [26]. The solar salt mixture presents the most interesting option for molten salt energy storage.

## **7. Cost of Molten Salts**

Cost is fundamentally the biggest driver in salt selection, at least for commercial systems. For tower systems, having a low-cost storage system can actually lower the levelized cost of energy (LCOE) from the plant compared to not using energy storage at all. The cost of storage can be less than the incremental cost of a larger power block to handle incremental additions to solar capacity.

However, storage can also add value to produced power through immediate accessibility and time of day delivery. Storage can also be useful with trough systems where the lower differential temperature requires several times more salt for a given MWh capacity.

An example of the importance of even small cost changes as a driver in salt selection is solar salt. While the freezing point of the nitrate salt mixture could be reduced slightly by using the NaNO<sub>3</sub>/KNO<sub>3</sub> eutectic (about 50/50 by weight), solar salt is specified as 60/40 by weight because NaNO<sub>3</sub> is approximately 30% cheaper than KNO<sub>3</sub> [29]. A more extreme case is the potential use of LiNO<sub>3</sub> to reduce the salt freezing point to about 120 °C by using about 30% LiNO<sub>3</sub>; since lithium nitrate can cost upwards of an order of magnitude more than NaNO<sub>3</sub>, it is not at all practical from a cost perspective.

**Table 4** Costs of solar salts [30].

Compound or mixture	$\Delta T$ ( $^{\circ}C$ )	Cost of salts (\$/kg)	Cost of power (\$/kWh)
Hitec XL in 59% water (42:15:43 Ca:Na:K by weight)	200	1.43	18.20
	200	3.49 (w/o H <sub>2</sub> O)	18.20
Hitec (7:53:40 NaNO <sub>3</sub> :KNO <sub>3</sub> :NaNO <sub>2</sub> by weight)	200	0.93	10.70
Solar Salt (60:40 Na:K Nitrate by weight)	200	0.49	5.80
Calcium nitrate mixture dewatered	200	1.19	15.20
(42:15:43 Ca:Na:K Mixture by weight)	150	1.19	20.10
	100	1.19	30.00
Therminol VP-1 (Diphenyl biphenyl oxide)	3.96	100.00	57.50

Availability of the MS in large quantities is commercially critical. Nitrates are mined materials, although now are also produced synthetically from carbonates, typically used in huge quantities as fertilizers, which allows large scale concentrating solar power (CSP) development with storage. Lithium nitrate is an excellent ternary additive to reduce the salt mixture freezing point without impacting high temperature stability, however it is in much shorter supply and much costlier.

The most effective molten salt to use in molten salt energy storage, when compared to the other salts, is the solar salt mixture (60% NaNO<sub>3</sub> + 40% KNO<sub>3</sub>). This is because solar salt compares favorably against other salts in terms of thermodynamic and heating properties, which are important factors to consider for molten salt use.

The costs of various types of salts must also be considered as well the thermophysical properties. The solar salt mixture is compared to various commercially available solar salt substitutes in Table 4 [30].

Based on both purchase costs and production costs, solar salt mixture (60% NaNO<sub>3</sub> + 40% KNO<sub>3</sub>) is the least expensive salt, costing 49 cents per kilogram to buy and \$5.80 per kilowatt-hour of power to generate [30]. At 93 cents per kilogram to buy and \$10.70 per kilowatt-hour to produce power, Hitec mixture is the next least expensive salt [30]. Meanwhile, at \$100 per kilogram to buy and \$57.50 per kilowatt-hour to produce power, Therminol VP-1 is the most expensive [30].

In order for a typical CSP plant, without MS, to produce the same amount of energy one with MS storage, the CSP plant would have to add equipment, including a second power block such as a steam generator, which would double the power block cost. Another way would be to double the solar power block size. This would increase the cost by 65% based on the 0.7 power law estimate for scaling turbine and generator costs. Another way to accommodate the additional solar energy would be to add MS storage to hold that additional thermal energy for use at times the power block was not otherwise fully utilized. It becomes therefore obvious that the Levelized Cost of Energy (LCOE) favors the use of molten salt storage.

Note that plant economics can be helped in other ways by MS-ESSs. Plant operations can be simplified and efficiency improved by always running the power block at full power, as well as having more efficient receiver operation through solar transients compared to a water/steam receiver, which will drop offline during a cloud outage and require significant time to bring back on line. More importantly, MS storage can provide a significant increase in value of the power generated during high demand periods when there is no sun, which is more valuable to the customer than power delivered during low demand periods, such as the mornings. The use of MS storage is quite beneficial when the LCOE is considered because the increased value of power and increased utilization of the power block still drive the economics favorably for storage [31].



Relative to the potential of other salt options, limitations on peak system temperature resulting from salt instability for nitrites and calcium nitrates, for example, would result in lower power block efficiencies, as well as higher storage costs because of decreased temperature differentials. Use of more expensive salts (LiNO<sub>3</sub> costing up to 10 times NaNO<sub>3</sub>, for example), would also change the storage cost balance from positive to negative [29].

## 8. Conclusions

A survey of various molten solar salts for use in energy storage shells is presented detailing their thermophysical properties, and costs, with the characteristics of these molten salts presented in tabular form. A history of molten salt usage is discussed, including their initial usage in nuclear energy production, further developments in molten salt nuclear reactors, their usage in solar energy storage and production, and their present and future developments in nuclear and solar energy storage and production. Recommendations for the selection of an economical molten salt compound are made using various characteristics, including melting temperature, thermal capacity, cost, and availability of the salts [1].

While not ideal from the perspective of melting point and thermal conductivity, based on all the other parameters above, solar salt (60 wt% NaNO<sub>3</sub>, 40 wt% KNO<sub>3</sub>) has been the choice for essentially all commercial CSP storage systems to date. Nitrite-based materials (e.g., Hitec: 40 wt% NaNO<sub>2</sub>, 7 wt% NaNO<sub>3</sub>, 53 wt% KNO<sub>3</sub>) could be suitable for lower temperature systems (up to about 450 °C), while chloride-based materials have future potential to be useful in higher temperature systems. Note that solar salt and nitrite-based materials are very well understood for CSP applications, and thus present little risk. New materials would require extensive testing, including large-scale testing, prior to being accepted by the CSP industry for commercial use.

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