# How Molten Salt Reactors and Thermal Desalination Could Transform Jordan

By:
William B. DeOreo, P.E., M.S., Aquacraft, Inc. Water Engineering and Management
John Kutsch, V.P Terrestrial Energy, U.S.A

**Abstract**
Advances in nuclear reactor design have occurred during the last few years, which make it possible to revisit the concept of nuclear power and water production for Jordan first proposed by Alvin Weinberg in 1963. The Kingdom of Jordan plays a key role in the Middle East as a safety zone for refugees and an island of stability in a troubled area. This status, however, is being threatened by large influxes of people fleeing civil unrest in Syria, Iraq and elsewhere. This increase in population has led to a situation where water and power shortages are endemic. Jordan is already one of the most water-short countries in the world with total water supplies available for all municipal uses of just over 400 MCM (243 lpcd)[1], and electrical generation capacity of only 0.44 kw/person, compared to the United States with average municipal water diversions of 57,670 MCM (530 lpcd)[2] and per capita power capacity of 3 kW/person[3]. Most of the water in Jordan comes from non-renewable or diminishing sources, and almost all of the electricity is generated by power plants using imported fossil fuels.

There is a small amount of desalination occurring in the country using reverse osmosis, and there are plans for increasing this to nearly 240 MCM per year by means of the Red Sea/Dead Sea project. Even with this project and all others currently planned, however, the Kingdom is anticipated to have water shortages of at least 100 MCM by 2030, and that is assuming all new projects can be completed as planned, and existing water supplies are not reduced by drought or other factors.

This paper describes an alternative system of water and power that is based on modern advanced nuclear reactors coupled with thermal distillation plants for producing both power and water. The key to the system is that the power reactors are not based on standard pressurized water and solid fuel reactors that make up the majority of plants currently in operation, but on molten salt reactors that do not use water for cooling, rely on liquid fuel, operate at high temperatures and low pressures and are generally safe enough to locate in places where their heat and power are needed. These characteristics make molten salt reactors ideally suited to a location such as Jordan.

When the waste heat from the power reactors is used to drive thermal desalination plants approximately 1 MGD (3,785 CMD) can be produced per 10 MW of electrical output. So a 1000 $MW_e$ power plant using molten salt technology could generate approximately 7.5 million MWh of electrical energy and 138 MCM of fresh water per year. Such a plant, by itself, would add 25% to the electrical generation capacity of the country, and provide enough fresh water to eliminate the water shortages through the middle of the century. The paper shows that the costs for this system are economically competitive. In addition, we explain why molten salt reactors can be safely built near the Red Sea and operated economically without fear of proliferation or accidental releases of radiation. The challenge will be to convince both decision makers and the public that such a system could actually be built and operated.

## Introduction
In a recent publication on water in the middle east, the author states that “more than two thirds of the earth’s surface is covered by water, but over 97 percent resides in oceans, inaccessible for human use

[1] Strategic Master Plan for Municipal Infrastructure, ( 2015). Table 3.9. Average supplies for 2013,2014 were 403 MCM, and population was 9.5 million persons
[2] USGS, Water Supply Paper, 2010. Shows average diversions for public supplies in U.S. at 42,000 MGD, population was 300 million persons.
[3] World Fact Book, Central Intelligence Agency. 4200 MW (2014) and 9.5 million residents (2016)

except at prohibitive cost."[4] Upon consideration of the current state of desalination technology, this statement, that ocean water must be considered inaccessible for human use, is clearly wrong. Even if one uses the most energy intensive system for desalination, which is reverse osmosis, the average energy required per thousand gallons (kgal) is approximately 15 kWh. At 10 cents per kWh this comes to a cost of $1,5/kgal, which is well within a reasonable cost for potable water. If, however, one uses thermal distillation of water, in combination with power generation, the waste heat from the power plant can be used to desalinate water, which makes this essentially free energy. The central problem in this system is how to obtain the energy for the power production. Fossil fuels are expensive and polluting, and renewable sources such as wind and solar are too diffuse and intermittent to meet the constant energy needs for a desalination system. Conventional nuclear reactors have their own problems with high costs, safety concerns, waste management and weapons proliferation. Does this mean that we must abandon the concept of cogeneration except in energy rich areas? Fortunately this is not the case since the rediscovery of an idea for nuclear reactors from the 1960's, which is liquid fuel molten salt reactors. This technology radically changes the entire concept of reactor design, and offers the possibility of making nuclear energy practical once again.

The idea of using a combination of nuclear power stations with thermal desalination systems to provide water and power to the middle-east is not a new one. It was first suggested to President John F. Kennedy by Dr. Alvin Weinberg, then director of the Oak Ridge National Laboratory (ORNL) in 1963. President Kennedy endorsed the idea, and Senator Howard Baker of Tennessee shepherded Senate Resolution 155, which put the weight of the U.S. Congress behind the concept.[5] For a number of reasons, which are beyond the scope of this paper, the concept never bore fruit, and no co-generation using nuclear power plants was developed in the region.

In short, the key reasons why nuclear power and thermal desalination have never been implemented were that they were based on very large solid fuel reactors that were cooled with high pressure water. The costs of these reactors continuously rose as more and more technology and complexity was added. in order to engineer safety to an inherently unstable and inefficient system. These reactors, that were originally designed to power ships, must contain steam at over 80 atmospheres of pressure and because of the limits of solid fuel they can only consume 1% of their fissionable fuel before the fuel assemblies need to be removed.

The solid fuel cycle on which they rely is inefficient and requires continuous reprocessing and handling of nuclear material that could, theoretically, be diverted for weapons production. So, safety, economy, and concerns over weapons proliferation were all key reasons that the first generation of nuclear reactors were never implemented in the middle east, even though the benefits of power and water production were, and still are needed. Now, over 50 years after the initial concept of the marriage of nuclear power and water production, the technology of nuclear reactors has advanced to the point that the authors believe that serious consideration should be given to the concept.

Normally, one would think that new technologies should be developed first in advanced countries and then gradually transferred to less developed countries over time. However, in the case of water and power, the reverse may prove to be the case. In advanced economies such as the United States there are many options for generation of power and water, and these create major disincentives for innovation. As long as there are abundant stores of both fossil fuels and raw water, there is no reason to push the envelope, and no reason to fight the battles of public relations in order to employ new technologies, especially if these involve nuclear energy.

In Jordan, however, there are large and growing deficits in both water and power, and there are simply no good alternatives for their elimination. Continued use of imported gas and oil for power generation drains the country financially, contributes to increased carbon dioxide emissions, and is not sustainable for the long run. According to the Water Master Plan and latest water demand studies, there are expected to be water shortages amounting to at least 100 million cubic meter (MCM) per year by 2025 or 2030. These

[4] Starr, Dr. Joyce. "Israel Water Wars" 1996.
[5] Weinberg, A.M.. "The First Nuclear Era, The Life and Times of a Technological Fixer." AIP Press (1994)

are shortages based on conservative estimates of future water demands and liberal estimates of water supplies. Actual shortages could be much larger. It should be kept in mind that there are already significant water shortages in the country, and most water customers have only intermittent supplies of 1 day per week. This means that they have to rely on roof tanks or expensive water deliveries, to carry them over for the other days. Addressing increasing shortages by further curtailing service is not a viable option.

Fortunately, the Kingdom borders the Red Sea at Aqaba, and thus has access to virtually unlimited ocean water, albeit water that is saline. Desalination of sea water is not a radical technology. Both reverse osmosis and thermal desalination are practiced throughout the region and the world, but both technologies require large amount of energy. Reverse osmosis plants require up to 20 kWh of energy per kgal (1 kgal = 3.8 cubic meters (cm)). Thus to produce 100 MCM/yr of fresh water using reverse osmosis would require 526 million kWh of electrical energy. For a country already short of electricity this is a formidable obstacle without new power supplies.

The second fortunate occurrence for Jordan is that their water and energy crisis is occurring at what many knowledgeable observers consider the dawn of the Second Nuclear Age. This is the age of the "advanced" nuclear reactor. As will be described in this paper, advanced nuclear reactors offer many advantages over the first generation of reactors. Among these are economy, safety, and the ability to provide both electrical energy and heat for industrial processes, such as desalination of water. These reactors could be employed in a resource poor county like Jordan where they could replace existing fossil fuel electrical generation and provide new generation capacity plus additional energy for water production. This is a project that could be supported by the international community.

Jordan lies at a crossroads. It faces shortages in both water and power generation, while it is also being expected to absorb large influxes of refugee populations. Many of the conflicts that led to refugee migrations were related to shortages of water which forced in-country migration from rural to urban areas because people could no longer make livings at agriculture6. A similar situation is also occurring in Jordan, where many Jordanian citizens are also moving into cities from rural areas, in addition to new arrivals from Syria and elsewhere. Water management and water conservation can help forestall crises, but by itself no amount of management can eliminate the fundamental problem of lack of adequate supply. If, however, the country embraces the marriage of advanced nuclear power stations with thermal cogeneration of fresh water the situation can be stabilized allowing for development of an advanced economy.

**Water Supply Projections for Jordan**

The water supply master plan for the Kingdom identifies four major sources for municipal water: shallow or alluvial groundwater, deep or confined groundwater, surface water and water from desalination. The alluvial water comes from various shallow aquifers lying along river valleys, such as the Jordan and Yarmouk Rivers. The deep groundwater will come primarily from the Disi Aquifer in the southern part of the country. The surface water comes from diversions from streams and rivers that may or may not be regulated by reservoirs. The desalination water is slated to come from the proposed Red Sea/Dead Sea project, which involves diversion of water from the Red Sea, running it to the Dead Sea lying below sea level, and using electricity generated from this drop to power reverse osmosis desalination plants and pump stations to send the water to Amman. As shown in Figure 1, the safe yields from these supplies is slated to reach its maximum of 730 MCM in 2025, nine years from today. This, of course, assumes no delays in project implementation or other issues that might interfere with successful implementation of the work.

[6] For example, see: http://www.voanews.com/a/drought-called-factor-in-syria-uprising/1733068.html

After 2025 the yields of all supplies with the exception of the desalination water, is assumed to decrease at approximately 1% per year to account for the effects of aquifer depletions and droughts.

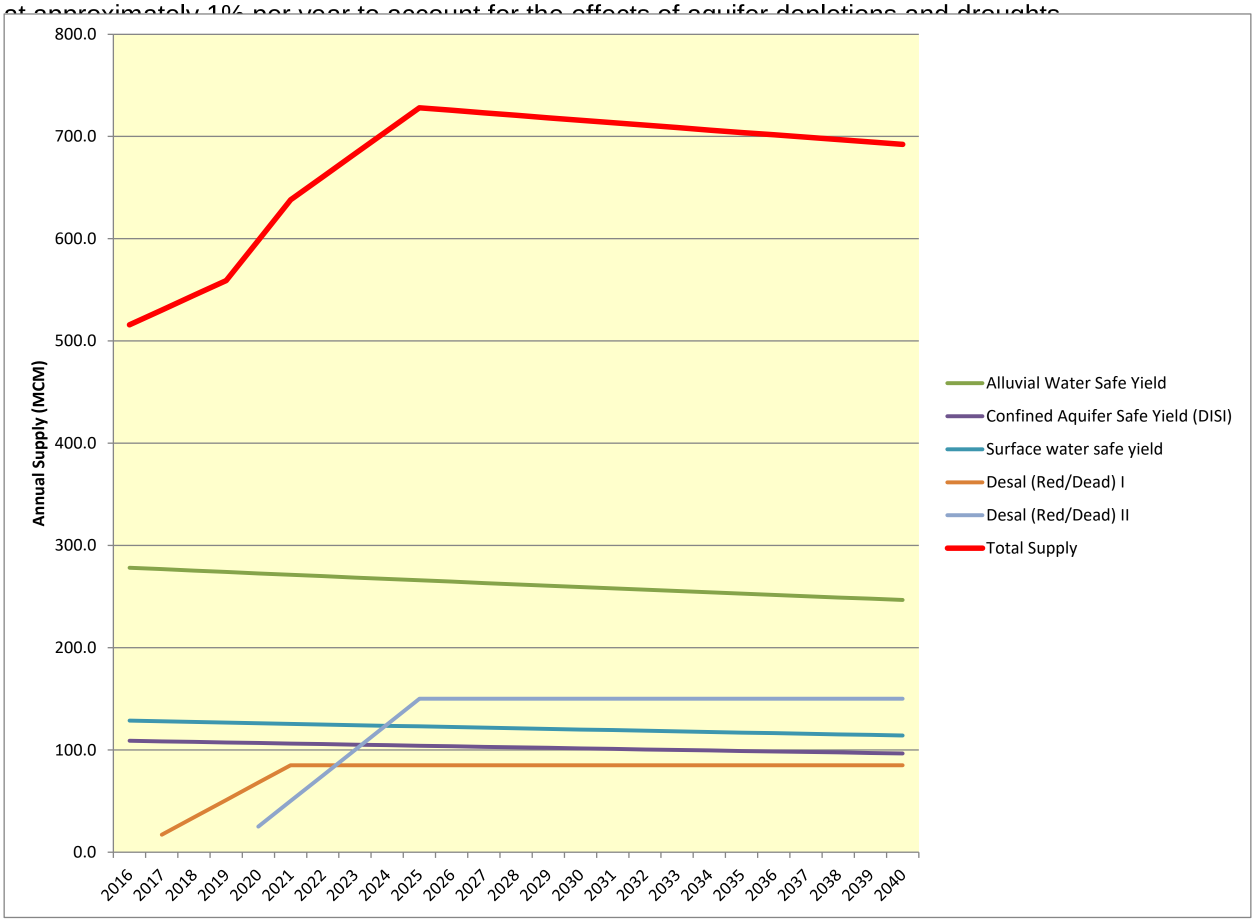



Figure 1 that reduce the surface water yields. This leaves a situation where the total water supply in the country that is available for municipal uses is expected to rise from its current level of approximately 515 MCM to 730 MCM in 2025, at which point it will gradually decrease, unless new supplies can be developed.

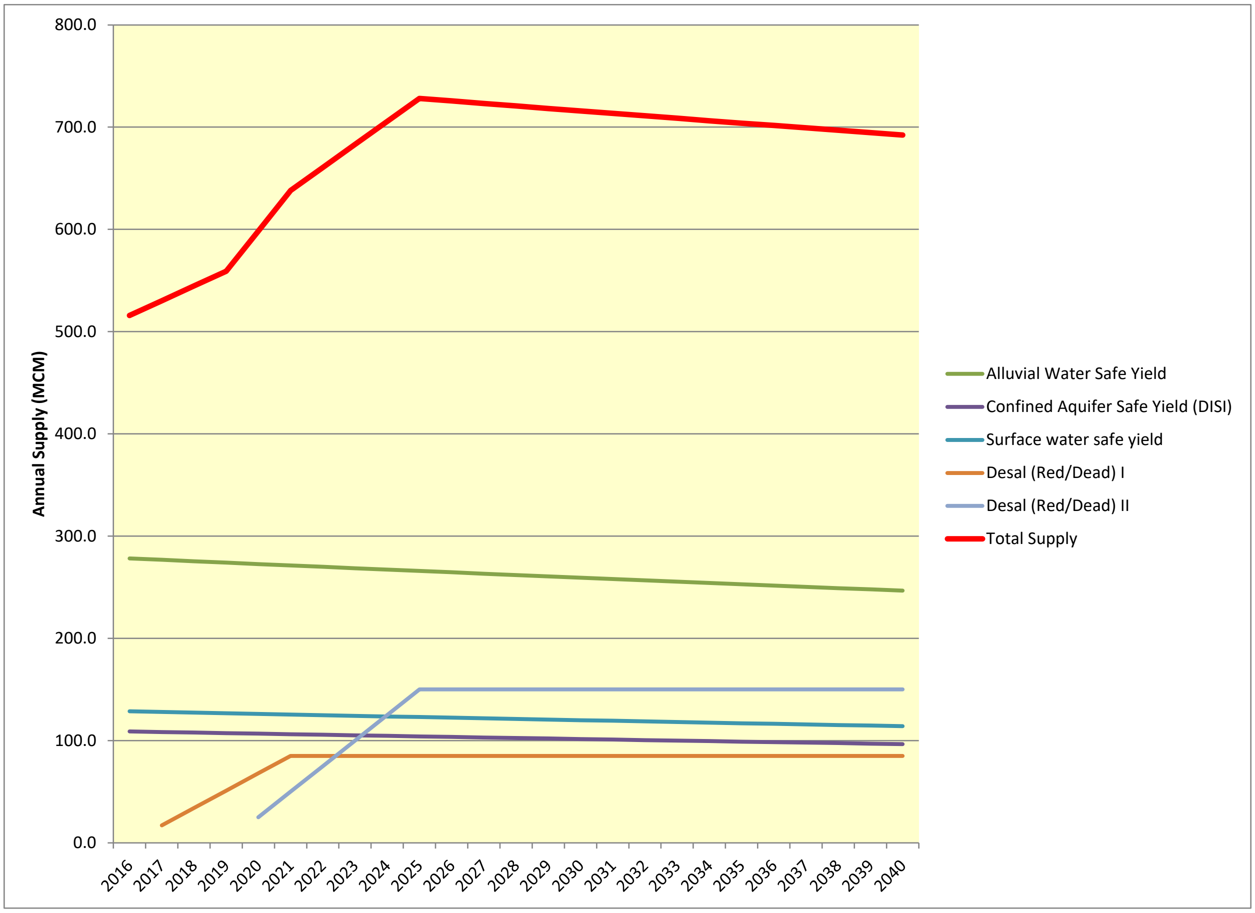



Figure 1: Optimistic Water Supply Projections for Jordan: 2016-2040 (source Water Master Plan 2016)

**Population Projections**

There are two driving forces behind water demands: the populations served, and the types of uses to which the water is used. Jordan has historically been a water short country, so most customers have been using less water than they normally would use if provided for a continuous water supply. Hence the lower per capita use in Jordan.

The population, meanwhile has grown faster than expected, largely due to the influx of refugees from Syria caused by the civil war occurring there. This fact is demonstrated in Figure 2, which shows the projected population as a solid line for Amman made in 2009 during the last water master planning project, and the actual population as of 2015 for the city. The actual population was 1.5 million persons greater than the official projections from 2009. Dealing with unexpected population increases of this magnitude would strain any water and power system, and is especially difficult for a system that was already stressed before the extra people appeared.

The new official population projections for the Kingdom are shown in Figure 3. These projections show the 2015 population of 9.5 million persons doubling to 19 million by 2050, or in 35 years. At the same time it is the stated policy to also increase the per capita water supplies so that each person in rural areas will receive 80 lpcd, each person in the municipal systems for Aqaba and Yarmouk will receive 100 lpcd, and each person in Amman, the capital city, will receive 120 lpcd. These deliveries are strictly for domestic (in-home) use. Additional water will be needed to make up for leakage, to supply industrial, commercial and institutional uses, residential irrigation of lawns and gardens and irrigation of public parks and open spaces. All of these water uses are critical for development of an advanced (first world) urban economy, and the resulting water demand projections derived from them are discussed in the following section.

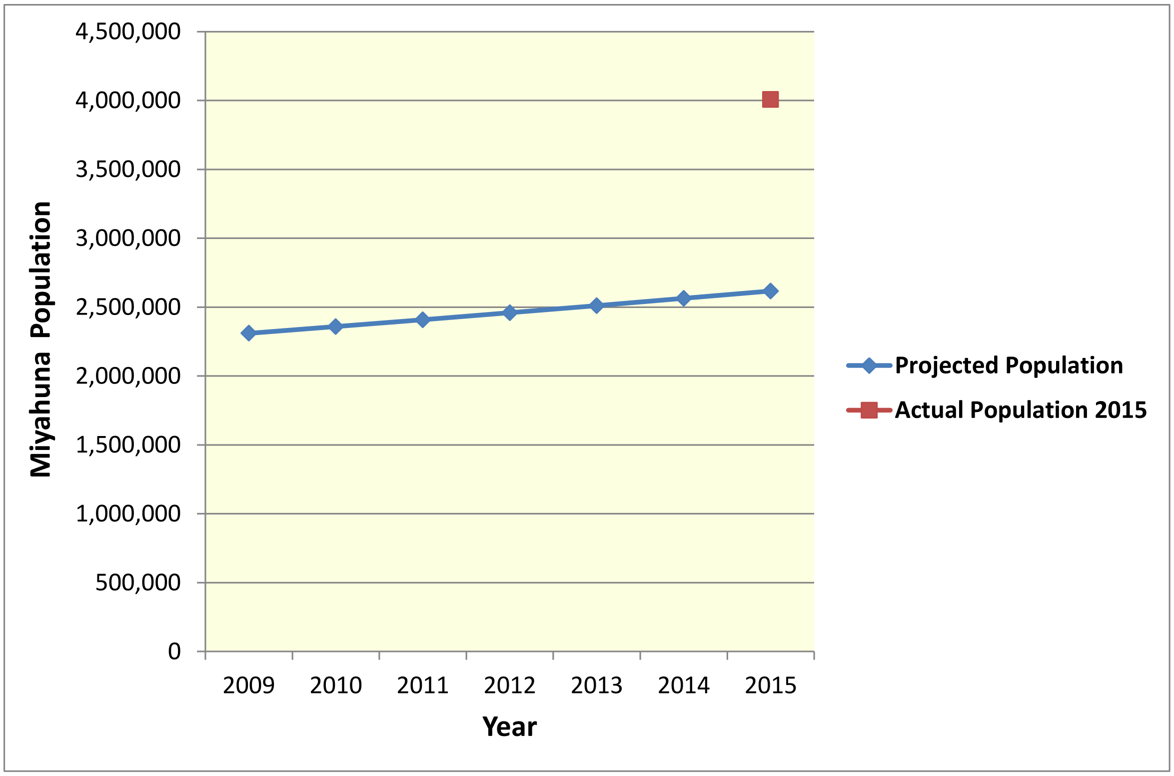



Figure 2: Actual vs predicted population for 2015 for Amman

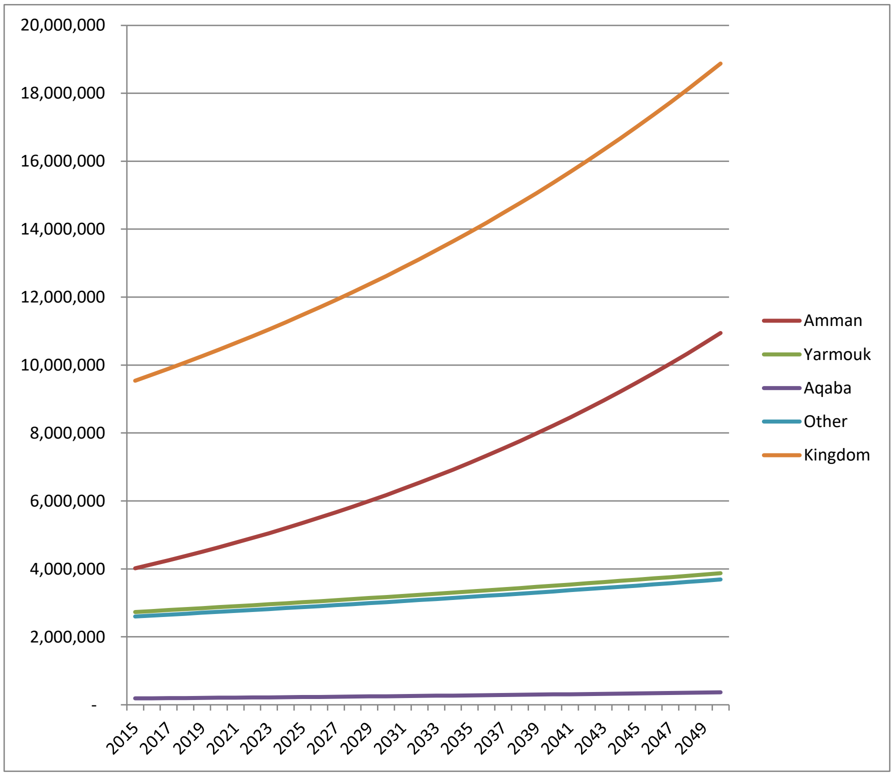



Figure 3: Population projections for the Kingdom of Jordan through 2050

**Water Demand Projections for Jordan**

A water demand forecasting model was created for the Kingdom of Jordan that allowed future demands to be projected for existing and new residential households based on their occupancy rates, efficiencies of fixtures and appliances and types of water uses occurring in the homes. The model operated over a 40 years study period and provided output on annual household and per capita water demands. In addition to residential uses, the model made allowances for water losses, irrigation (both residential and public) and ICI water uses.

There were two scenarios run that we believe are relevant to our purposes here. First was the intermediate scenario, which provided for increases for residential demands and made modest allowances for increased supplies for ICI and irrigation uses. The second scenario maintained the residential supplies, but provided more water for ICI and urban irrigation uses, such that the supplies would approach those from advanced economies.

Table 1: Demand parameters for scenarios

| **Parameter** | **Intermediate** | **Advanced** |
|---|---|---|
| **Domestic Use** | 80/100/120 lpcd | 80/100/120 lpcd |
| **ICI** | 30% of domestic | 50% of domestic |
| **Residential Irrigation** | 10 $M^2$ per household | 20 $M^2$ per household |
| **Public Irrigation** | 1% of domestic | 5% of domestic |

When the demand model was run with the above parameter values, and using the population projections shown in Figure 3 the resulting annual demands are shown in Figure 4. The projections show that in 2025 the total demands under the intermediate scenario will be approximately 650 MCM, and the advanced scenario will be 736 MCM, compared to projected maximum supplies of 730 MCM in 2025. Under these conditions the country will be either approaching or exceeding its anticipated supply by 2025.

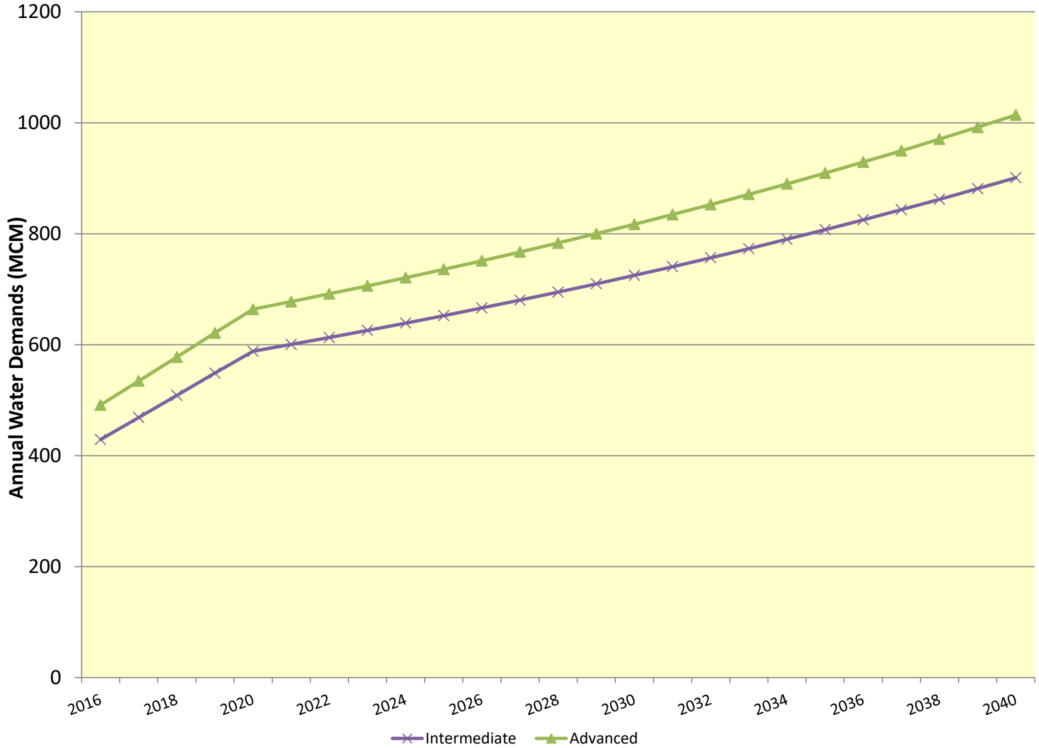



Figure 4: Water Demand Projections

**Comparison of Demands and Supplies**

If one overlays the graphs of demands and supplies it become apparent that the period between 2025 and 2030 is the critical one for water supplies, since this is the period when both demand lines cross over the supply line and water shortages become endemic. If the country aspires to having an advanced economy the year 2025 is when demands permanently exceed supplies. Even if only the intermediate demand scenario is planned for, the situation will become untenable around 2030. So the conclusion is clear that the period from 2025 to 2030 is the critical one for Jordan from the perspective of water demands, water supplies and shortages, which allows approximately 10 to 14 years to work out a solution.

It should also be kept in mind that virtually the entire new water supply projected for the Kingdom, approximately 240 MCM, is to come from two phases of a single project: the Red Sea to Dead Sea project. This is an expensive and complex project, and having a back-up plan for new water and power in the event that it becomes impossible to construct the Red-Dead project might be considered prudent.

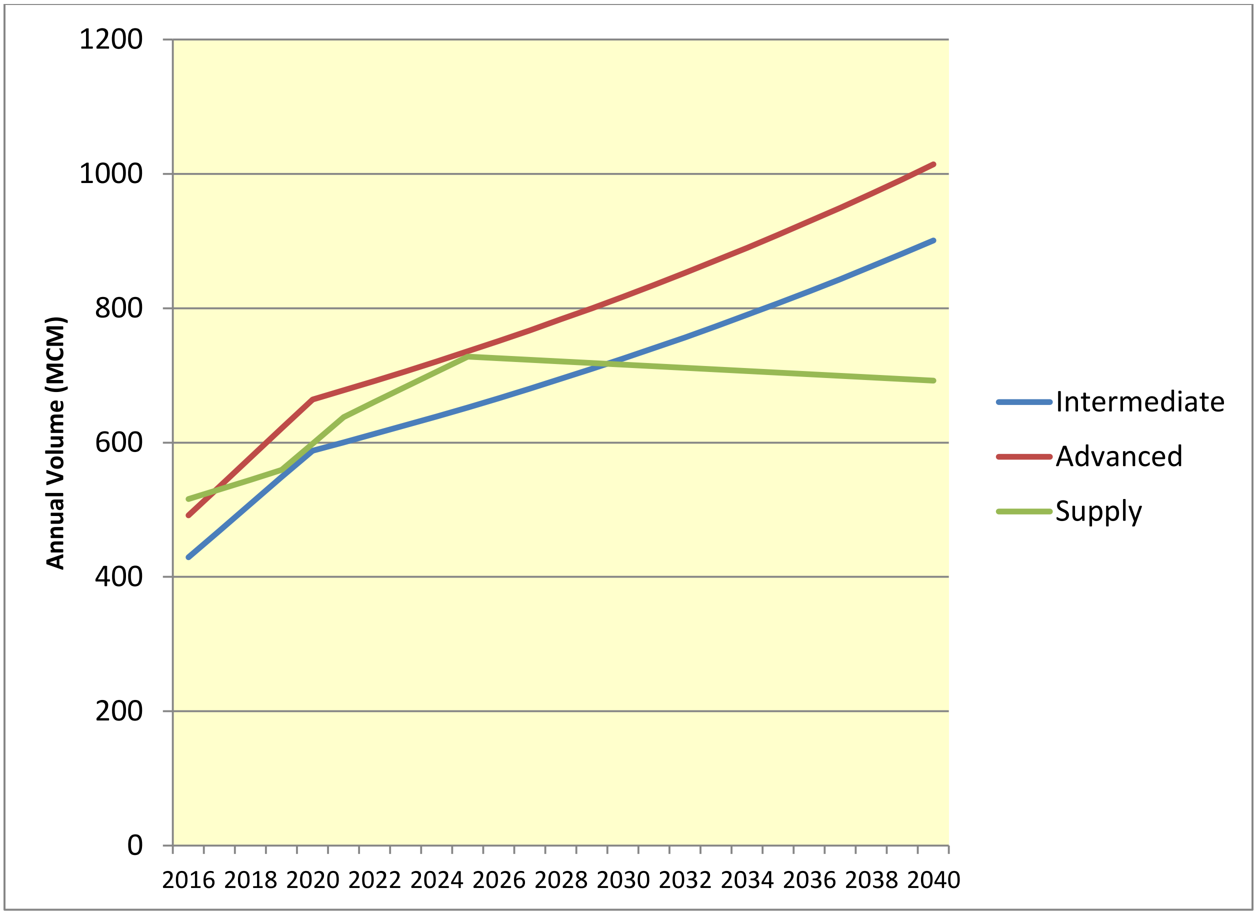



Figure 5: Comparison of demands and supplies for Jordan

**The Water Energy Nexus for Jordan**

Several years ago the term “Water Energy Nexus” became popular. The persons who used the term had apparently made a new discovery that there is a connection between water supplies and energy. There has always been a close connection between water and energy, going back to the time during which water had to be carried by animals or humans. The Roman empire created water engineering projects to convey water over long distances using open channels and gravity-flow aqueducts. The Romans, however, while the knew about steam devices, were never able to harness its power to pump water. If they had, then the empire might still be going strong. It was not until the nineteenth century, and James Watt’s invention of the steam engine, that large scale pumping of water became practical.

Today, vast amount of energy are used to collect, treat and transmit water for both municipal and agricultural uses. In the United States, the State of California devotes over 20% of total electrical energy production (48 TWh) to water.[7] In Jordan, approximately 14% of the electrical production (1.4 TWh) is used by the water sector just for pumping.[8] To the degree that this energy comes from burning of fossil fuels it contributes to carbon dioxide loading to the atmosphere and global warming, which in a vicious cycle exacerbates droughts and reduces water supplies.

While it takes energy to produce water, the inverse is also true: if one has energy it is possible to obtain potable water, but without energy its back to animals and gravity. Coal was the fuel of the nineteenth century, oil was the fuel of the 20$^{th}$ century, and we believe that nuclear fission will be the fuel of the 21$^{st}$

[7] See: http://www.energy.ca.gov/research/iaw/water.html
[8] National Water Strategy 2016-2025, Ministry of Water and Irrigation, (2016) see page 46.

century. With luck, nuclear fusion may power the 22nd century and beyond, but for the near term, fission power in advanced reactors seems like the best course of action. If humanity is able to overcome its fear of nuclear power, and develop the types of reactors that the original inventors of the technology advocated for civilian power production it can have virtually unlimited power for both electricity and industrial processes, such as desalination. For purposes of this discussion we will describe one advanced reactor design, the Integral Molten Salt Reactor, which is under development by the Terrestrial Energy Company, of Toronto Canada. Their design is well along the path for regulatory approval and commercial development, and we believe that this system high the very high likelihood of being ready for implementation within the time frame required by Jordan. The following sections describe what an integral molten salt reactor (IMSR) is, and how it is different from the conventional pressurized water reactors that have come to dominate nuclear power station design.

**What is an Integral Molten Salt Reactor (IMSR)?**

The most fundamental difference between molten salt reactors and pressurized water reactors is that they use a liquid fuel rather than solid fuel. In molten salt reactors the fissionable material that drives the plant is dissolved in salt rather than contained in a ceramic pellet. This greatly simplifies both the fuel fabrication and the operation of the plant. It also means that there is no possibility of a fuel core melt down, simply because the fuel is already melted under normal operation of the plant. In a solid fuel reactor the core is in danger of melting, while in a liquid fuel reactor in the event of a malfunction the fuel will solidify as it cools.

What distinguishes the integrated MSR (IMSR) is that all the components for the operation of the reactor are contained in one vessel. This is a huge advantage because it eliminates the need to convey the radioactive fuel through the wall of the reactor vessel. Any penetration of the containment vessel with pipes containing radioactive material is a built-in vulnerability.

In an IMSR the primary heat exchanger, reactor core, fuel salt and pumps are all a single "pool type" reactor unit that is replaceable every 7 to 10 years. The IMSR power generation facility is designed to have a complete new reactor unit installed every 7 to 10 years as well as much of the coolant salt system and secondary heat exchangers, instead of attempting a difficult and potentially dangerous on-site rebuild of a unit at the end of service life.

Rather than being a shortcoming, the core replacement is actually a great advantage since in exchange for the modest cost for reactor units and fuel salts every 7 years, the plant obtains the latest and best reactor design with most advanced materials and the operator essentially gets a freshly rebuilt reconditioned facility and newly inspected and refurbished balance of plant. This keeps expenses and down time very low and safety very high.

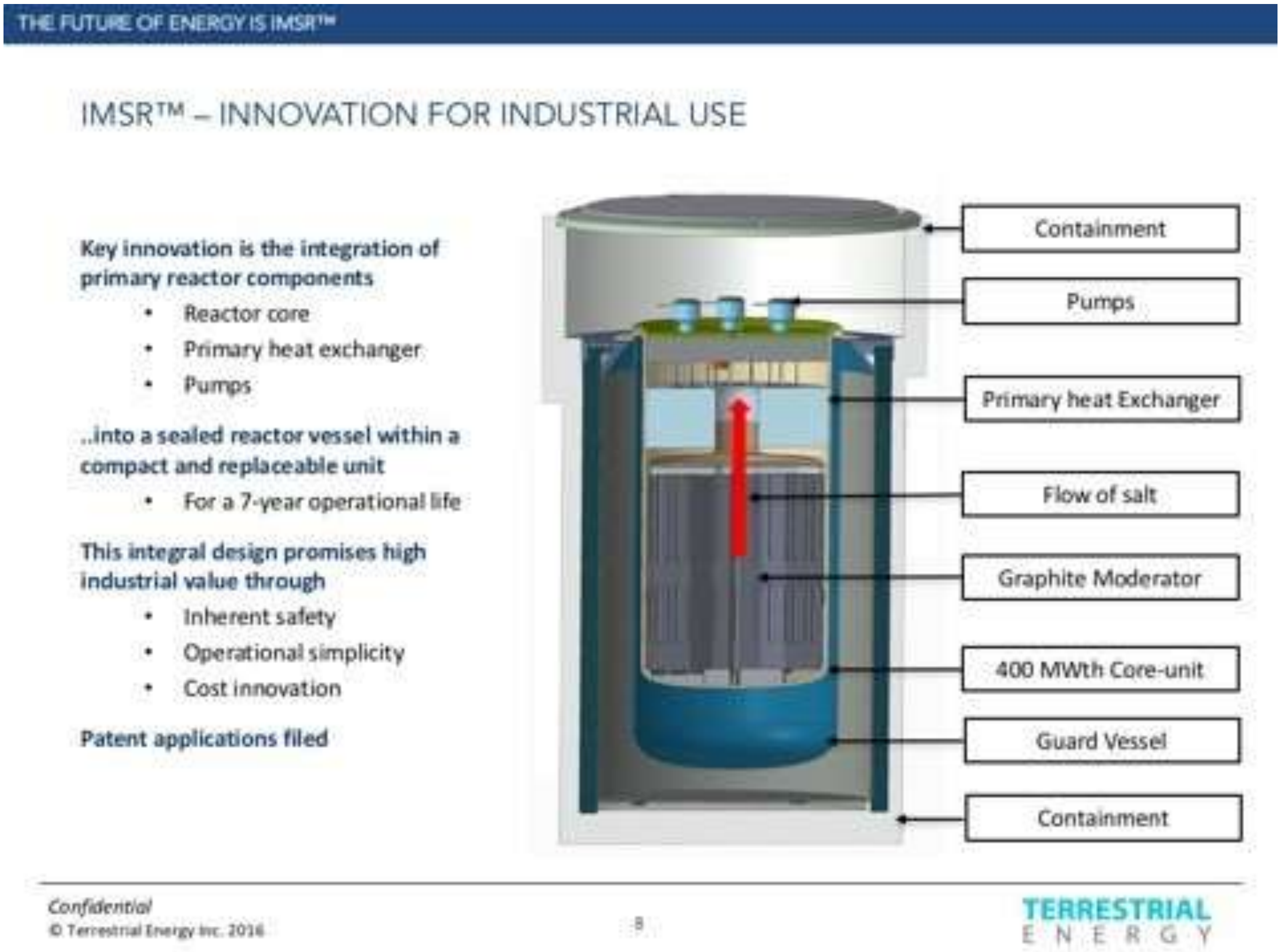



Figure 6: Schematic of 400 MW Integrated Molten Salt Reactor (Source Terrestrial Energy, Inc)

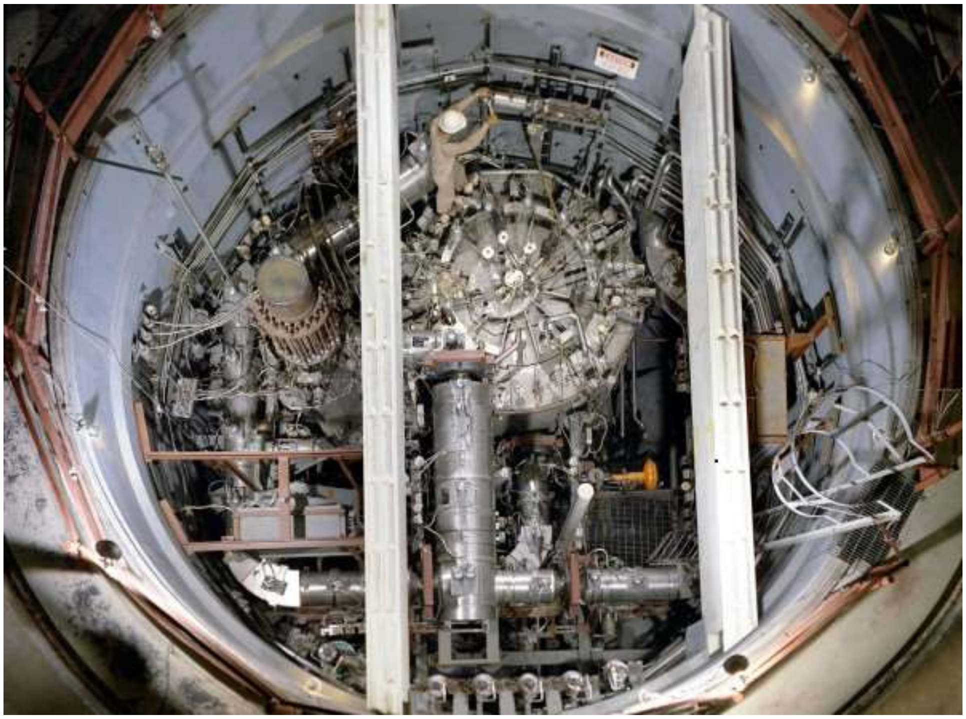
**The advantages of molten salt**

The original idea for using very stable high temperature salts instead of unstable water came from Drs. Eugene Wigner and Alvin Weinberg and the design group at Oak Ridge national labs. These renowned scientists and engineers understood that salts were nearly impervious to damage from high temperatures and radiation and could work well at atmospheric pressure, operating at 700 $^{o}$C for decades. The salts do not melt until 400 $^{o}$C and do not boil until 1500 $^{o}$C – they operate around 700C ]

This combination of traits for the MSR also provided the densest energy and highest grade process heat for electricity production and industrial uses – like desalination. Fuel salts do not need to be kept under extreme pressure like water, and they will not breakdown like Zirconium solid fuel rods. They did not need water to cool the MSR system, so the reactor could be put away from water in arid regions.

The original reason and idea for such a reactor was for use as a propulsion system for aircraft. Having a nuclear power source would allow these craft to stay aloft for extended periods, The aircraft idea was quickly found to be impractical, but the idea to use the design for civilian power production was seen to have many advantages.

In 1962 a commission told President Kennedy of the USA that this Molten Salt Recactor should be the reactor for civilian markets. Dr, Weinberg got permission to build the Molten Salt Reactor Experiment and that reactor ran for 22,000 hours plus an additional 3,000 hours of experiments – a most successful proof that this reactor was safe and effective.



This is the actual MSRE that ran for over 22,000 safe, clean hours


Alvin Weinberg congratulates the MSRE reactor Team

Fuel Salt is like water when melted

**What makes this an advanced design?**

When one compares the molten salt design to conventional light water reactors (LWR) the advantages of the IMSR become clear: they are safer, more economical and far more efficient.

Molten Salt Reactors have the core great advantage of being inherently “walk away safe”. This means that they do not require active intervention to shut down safely. An IMSR needs to be constantly held on to keep running otherwise it will automatically go into shut down mode. A light water reactor needs to be constantly adjusted and controlled or it will run out of control and can present a dangerous situation.

Another inherently safe aspect of an IMSR are that it is not cooled with water, which means it can operate at near atmospheric pressures. Low pressure operation means the IMSR is not only very safe but much less expensive to build and maintain. The huge steel and concrete containment vessel, that is the hallmark of light water nuclear plants, can be eliminated, along with the need for emergency cooling systems and back-up power and all of the other complications associated with the high pressure steam cooling system. Compared to the simplest light water reactor that has hundreds of pumps and thousands of valves a millions of points of failure that have to be constantly monitored – this makes Light Water hard to manage and expensive to build and maintain.

**Why makes the IMSR a better choice?**

The most important safety feature of a molten salt reactor is its ability to operate without water and at atmospheric pressure. This eliminates the danger of the cooling water flashing to steam if a pipe breaks or a valve malfunctions. The combination of high pressure steam and nuclear fuel rods is a dangerous one that molten salt reactors directly address.

The reason that LWRs can create explosions is that when the fuel rods are exposed to air and steam in a loss of coolant accident the Zirconium cladding generates hydrogen gas. It was hydrogen that caused the explosions at Fukushima, not the actual reactor cores. An IMSR, however, is incapable of this type of event because there is no steam or Zirconium to generate hydrogen. There is nothing in the system that is pressurized, and none of the chemicals are flammable or reactive with water.

Molten salt reactors are highly resistant to radioactive contamination. The two bye-products that present the main danger for spread of radioactive contamination in a nuclear reactor accident are Iodine and Cesium. In a LWR these accumulate as gasses inside the fuel pellets. If the fuel pellets melt in an accident then the radioactive Iodine and Cesium escape to the atmosphere. These can then spread over wide areas and expose the population to radiation. In a molten salt reactor these elements are bound up as stable salts, which cannot escape to the atmosphere. This eliminates the major source of potential contamination.

Molten salt reactors generate a fraction of the waste produced by a LWR . The main reason that the LWR design generates so much waste is that the solid fuel can only be used for a short period of time before it must be removed due to contamination. After “burning” only a few percent of the fissionable material the rods contain both high level (fissionable) and low level (decay products) waste products, and these rods need to be stored for very long periods of time or reprocessed. In a MSR the fuel is liquid, so the contaminants that force the solid fuel rods to be replaced can be continuously removed. This allows the high level fissionable “wastes” to be left in the reactor where they can continue to serve as fuel. At the same time much of the low level bye products can be extracted for sale for scientific, medical and industrial uses. All of this is possible because the use of liquid fuel is inherently a more efficient way to operate a chemical system.

Finally, a critical advantage of a molten salt reactor and especially the IMSR is that there is virtually no practical chance that the reactor can be used for weapons development. The IMSR comes with fuel already in place, and is removed for reprocessing at the end of its life span. After operating for 7 years most of the nuclear material has undergone fission and the inventory of weapons grade material is very low. Plus, to the extent that there is any weapons grade material in the mix there are also isotopes which make it impractical to use for weapons. The IMSR design is also compatible with future versions that will run on Thorium rather than Uranium, and breed their own fuel, which has even less weapons potential.

I WOULD SHOW THE VIDEOS OF HOW THE IMSR WORKS AT THIS POINT IN A PRESENTATION (If we have enough time allotted during the presentations that would be great.)

Molten salt reactors are ideally suited to Jordan and other places that are water short. A conventional reactor requires large amount of water for cooling, and any interruption of the water supply will create a serious safety issue. A MSR, however, is cooled by molten salt, and in the event of a reactor shut down the salt solution will safely cool down passively. So even if there is a total power outage or major natural disaster such as an earthquake the system will safely remain stable.

The only water that an MSR requires is the water used for running a steam turbine to generate electricity. This water would form the secondary loop, taking heat from the primary molten salt heat exchanger, converting it to steam, and running the turbine. From here the waste heat exiting the turbine would be used as source heat for the multiple effect distiller (MED). Make up water for the steam turbine will be supplied from the product water from the distillation system. The high operating temperature of the reactor, at 600 $^{o}$C or more provides ample energy for both power and water production. Conventional LWRs operate at much lower temperatures, and cannot be as efficient for co-generation.

**It is possible to construct an IMSR at Aqaba by 2030**

As mentioned above, the molten salt reactor is not a theoretical concept, but a proven technology. A proof of concept reactor using molten salt was operated at Oak Ridge National Laboratories for over 20,000 hours. This reactor worked and showed that it is possible to build and safely operate these systems. While work on MSRs was suspended for many years, there is now increasing interest in the technology, and several companies are working on designs based on molten salt in several countries. The design by the Terrestrial Energy, Co, seems to be one with a very good chance of getting a reactor on the market soon, and we have used this as our prototype for this paper.

In the Terrestrial Energy (TE) design the entire plant is designed to be modular and shipped to the site for final assembly. Every component and material is chosen to be readily available and easily deployed and used. Terrestrial is not using exotic metals or systems. The pumps and heat exchangers are being developed and going through approval in Canada and soon the USA. All support systems and balance of plant are commercially available systems, such as a Siemens SST5000 generator system. Most importantly, the fuel of choice for the TE system uses the already licensed Uranium, which greatly simplifies the regulatory hurdles.

The TE nuclear hall is built in a factory in pieces and shipped as membrane wall components to the site to be welded and filled with nuclear concrete. Because the system is not pressurized and can't explode, there is no need fo have pressure buildings requiring millions of pounds of steel and concrete and rebar. Everything can be made as modular metal factory based pieces that arrive onsite on trucks fully inspected. All the rest of the buildings are precast concrete and are also produced in a factory and then site assembled.

The reactor cores are likewise built in a factory and shipped to the site where they are then fueled and operated. The reactor core comes as an integral unit, and after its life cycle is complete it is shipped back to the factory as a sealed unit for refurbishing.

The modular construction lets the systems become better made, more consistent, higher quality, continually improved and most of all, through economy of scale, the entire IMSR system is inexpensive because of this. You can site a single 400 MW unit on just a few acres. A 4 unit system could be built on as little as 40 acres. The anticipated time to construct a plant, such as the one shown in Figure 7 is 2 years. At this time the manufacturer plans to have units ready to ship by ______________.

Figure 7: Integral MSR 400 installation

**Economic Analysis**

A conceptual economic analysis of the project was done in order to determine its feasibility. The project included the following items:

- 1000 MWe molten salt reactor with steam generation at $4/watt total CapEx ($2/watt for MSR + $2/watt for electrical generation)
- 100 MGD thermal distillation plant using multiple effect distillation at $5/gpd CapEx
- Allowance for diversions, pretreatment and post treatment of distilled water ($18 million)
- Energy allowance of $115 million for pumping product water from Aqaba to Amman through existing DISI pipeline, which will have available capacity as the yield of the aquifer decreases. At some point, a second 5' pipeline could be run parallel to the existing pipeline, but these costs are not included here.
- The total capital cost for the combined power and water project would be $4.5 billion.
- 30 year financing at 3.5% with $500 million interest during construction
- 10% allowance for contingencies and design
- $50 million allowance for annual operations expense for MSR and MED plant
- $4.5 million/year allowance for refueling the MSR on 7 year schedule
- 15% contingency for annual expenses
- Income from power production based on $0.1/kWh and from water sales at $6/kgal (JD 1.11/cm)

The result of this analysis showed that the project would have average annual costs of $464 million and generate annual income of $850 from water and power sales. This represents a net annual B/C ratio of 1.83. This does not include any income from sale of wastewater generated by the project for agricultural users, which has potential. It also assumes that the water users of the country will be able to pay $6/kgal or JD 1.11/cm for water at the margin. The current marginal cost for water based on average residential use patterns of 0.6 cm/day, and the 2015 tariff structure is 0.5 JD/cm. While this represents a significant increase we know that the current water rates are subsidized. The costs projected here do not include any subsidies, and given the alternative of chronic shortages, they seem like a manageable price to pay. At this rate the average annual cost for water for the typical household would be less than $1/day.

**Summary and Conclusions**

The country of Jordan is facing severe shortages in both water and electricity. These shortages are projected to become acute by the middle of the next decade as the population rises and water and power resources decline. Shortages of this kind can create economic and civil disturbances that threaten the stability of the county and the region. If water supplies are not sufficient to support the population, there will be an exodus and a new wave of eco refugees created. In order to forestall this situation it is in the interests of the international community to assist with development projects that enhance both water and power generation.

This paper describes a cogeneration project that could deliver over 6.3 million MWh of electrical energy and 112,000 acre feet of water (137 million cubic meters). Rather than using fossil fuels for the source the project, which would all have to be imported, this project would be based on advanced nuclear power using liquid fuel, molten salt reactors. We explain that the benefits of these devices include their safety, economy and environmental compatibility.

Construction of the project would not be inexpensive. Total capital costs are estimated to be in the vicinity of $4.5 billion with total annual costs for both debt service and O&M amounting to $465 million. The income from the project, however, would be greater than the costs. Annual income from water and power sales are estimated to be $850 million, which amounts to a B/C ratio of over 1.8.

When considering projects of this kind we need to factor in the cost of Jordan running out of water and power, and what impacts this would have in terms of economic dislocations, unrest and possible war. Providing water and power is a way of securing a stable and prosperous economy for Jordan, and is certain to be far more effective than attempting to deal with a catastrophe after it happens. Jordan may be the perfect place to demonstrate the feasibility of use of advanced nuclear technology for power and water production since they have such a great need and have so few other viable options. Jordan also has a strong government and a well educated population that could manage a system such as this.