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RESEARCH ARTICLE OPEN ACCESS

Produced Water Treatment Utilizing Process Heat from High Temperature Gas Cooled Reactor (HTGR) in Permian Basin

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ABSTRACT

When settlers first occupied west Texas in the 1800's they believed that the underlying "Ogallala Aquifer" had the capacity to provide a more than an adequate supply of the residents' fresh water needs. The Ogallala is beneath the surface in the following: West Texas Panhandle, far eastern New Mexico, Oklahoma Panhandle, western Kansas, eastern Colorado, western Wyoming, southern South Dakota, and most of Nebraska. Large-scale extraction of water from the "Ogallala Aquifer" for agricultural purposes started after World War II, due partially to the development of the "centre pivot" irrigation technology and the adaptation of automotive engines for pumping water from groundwater wells.[1] Today about 27% of the irrigated land in the entire United States lies over this Ogallala Aquifer, which yields about 30% of the ground water used for irrigation in the United States.[2] However, the Aquifer is presently at risk for both over-extraction and pollution.

Currently used horizontal drilling techniques and subsequent "fracking" are enhanced production methods that are efficient in extracting hydrocarbons. But they have a significant "down-side" in that they require the use of an average of 3 to 4 million gallons of "fresh" water per well for horizontal drilling and about 5 million gallons of water per well for fracking!" In fact, this water use significantly contributes to the current state of the Permian Basin's "water stress." Degradation of the fresh water supply in Permian Basin has become a reality as we have discovered that when we produce increasing amounts of hydrocarbons, it is at the expense of our clean water reserve!

The concept presented in this paper is transformational since it is utilizing two gigantic/effective energy entities in addressing and ascertaining energy security for the US. It is a model which integrates "oil and gas" and nuclear entities to address the water management issue in US and globally.

The U.S. and international nuclear energy industry are a capable generator of electricity. In addition, it also has the capacity to treat 1) produced water from oil and gas (O&G) production, and 2) brackish ground water, to "drinking water quality" standards at a cost of ~$0.35 per "barrel" (or less than a half a cent per gallon). This would not only improve the efficiency of the O&G production industry through the utilization of "clean" water sources, it would also re-establish the fresh water resources that have been polluted by the O&G industry and agriculture over the past 50 years or so.

The attractive economic aspects of this process indicate a significant cost reduction in the treatment of O&G "produced water" and a potential path to recharge fresh-water aquifers in the west Texas Permian Basin that have been polluted by agriculture and the oil and gas industry.

This facility can create clean drinking quality water for either human consumption and/or industrial applications (1e, O&G production). Technical studies and analysis throughout the world have also determined that this "High-Temperature Gas-cooled Reactor" (HTGR) design to be used for this facility, is designated as being "Inherently safe" by the US Nuclear Regulatory Commission because the reactor is safely controlled by the "laws of physics" rather than decisions and/or reactions made by man!

The $1.5 to $2.0 billion-dollar facility will use the 1700^o F "process" heat from gas-cooled nuclear reactors to treat "produced water." This treatment, or cleansing, of the produced water will make it more effective for use in hydraulic fracturing and drilling purposes. In addition, this process can also increase the supply of potable water (water for human consumption and other high-temperature industrial applications) in arid regions like the Permian Basin of west Texas. This technology should also substantially decrease the amount of produced water injected into disposal wells in the Permian Basin, thus mitigating the potential risk of induced seismic activity in the region.

The table below summarizes the economics developed by industry and the DOE. In each case the output stream is "drinking quality" water plus brine and "waste" (which would be sent to a "disposal well" in the O&G producing regions of the Permian Basin).

	$/BBL	$/gal
Lowest Price	$0.16	$0.004
Highest Price	$0.60	$0.014

Table 1: Price Range for Produced Water Treatment[29]

We believe that the above estimated costs make this technology a profitable solution to either a) create a sustainable fresh water supply for human consumption from brackish water, and/or b) treat produced water from regional O&G operators to enhance the quality and efficiency of the fracking and subsequent production process in the oil and gas industry.

Keywords: Agriculture, Produced Water, Water Treatment, Nuclear Reactor, Oil and Gas, Environment, Fracking, Energy Flow, National Security

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I. INTRODUCTION: HUMAN NEED & SCARCITY

This report specifically addresses the development of a more efficient manner to handle the "produced water" from oil and gas in wells drilled in the "Permian Basin" of West Texas, and more specifically in Ector and Midland counties.

The Permian Basin is currently experiencing the phenomena known as "water stress" in many of their drilling and production operations. This phenomenon occurs when the demand for fresh water exceeds the quantity readily available to assist both the drilling and the production processes.

The primary working fluid in all phases of drilling and producing oil and/or gas wells are significant quantities of water. However, the available sources of the fresh water required for hydraulic fracturing and horizontal drilling are limited in the Permian Basin. Therefore, the intention of this report is to:

(1) Assess current quantities of both produced hydrocarbons and produced water
(2) Discuss the effects of future water shortages
(3) Determine the alternatives/remedy for the mid-term water shortage
(4) Perform cost analysis/discussion for the proposed water treatment
(5) Discuss measures to help prevent seismic activities that might occur in the region in the future due to increased water disposal.
(6) Draw conclusions and make recommendations on measures to address the near-term and future concerns of public health.

In the Permian Basin, hydrocarbon production always includes the so-called "produced water" during the entire life of all wells. The rate of water production versus oil production depends on several factors, such as the stage of hydrocarbon production, the life of the well, etc. On average, wells in the Permian Basin produce ~10 bbl/d [3] of water per bbl/d of produced oil. This produced water is currently disposed into geologic formations far below the producing zones for oil and gas.

With the use of nuclear reactors to treat the produced water in the Permian Basin, the oil and gas industry now has a safe and economic process to take produced water from O&G operations, and/or brackish water, and make it potable for human consumption, and much more suitable for enhanced production techniques such as "fracking" and horizontal drilling.

Figure 1 below shows the counties in West Texas that include the "Permian Basin." Odessa is in Ector County, which resides in District 8A for the Texas Railroad Commission regulatory purposes. Oil production in the Permian Basin has steadily increased from ~1 million barrels per day in 2011, to a peak amount of ~3.4 million barrels per day in 2018. The approximate corresponding volumes of water produced for this interval are between 10 millionbbl/d and 34 million bbl/d, based on ~10 bbl/d [3] of produced water per bbl of produced oil.

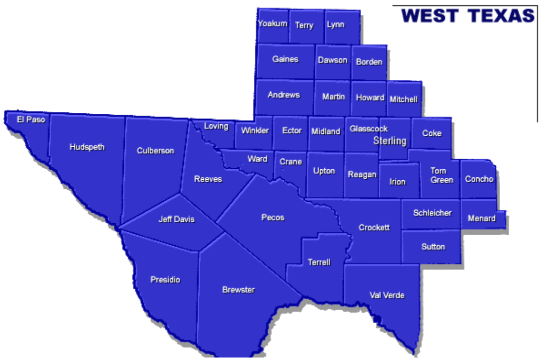


Figure 1 – Counties in West Texas known as the Permian Basin

II. LOCAL SOURCE OF SUPPLY DEMAND FOR WATER IN PERMIAN BASIN

Produced Water Volumes

Table 2 shows the produced water estimates based on water to oil ratio of 10:1 barrels/barrel in Permian Basin. Column 4 is the estimated volume in a one-year duration. As it is apparent from data, the produced water volume in the Permian Basin is a considerable amount that has historically been an expense for the operators, since this water was discarded by injection to disposal wells incurring transportation costs and disposal costs (with a cost of about half a million dollars to drill an injection well). However, in the last few years, some oil companies have started to treat the produced water as a commodity rather than a by-product of hydrocarbon production.

Year	Oil Production (10^6bbl/d)	Water Production (10^6bbl/d)	Estimated Total Produced Water Volume (10^9 bbls) per year
2011	1	10	3.65
2018	3.4	34	12.41

Table 2: Predicted Produced Water Volume

Below is typical "Operating" cost data relevant to discarding produced water in typical disposal wells in the Permian Basin.

Transportation cost($/per bbl/ mile)	**Transportation cost ($/per hour)**	**Cost by Piping ($)**	**Injection well cost (Operating $)**
$0.09	$90	$0.02	$500,000

Table 3: Typical Cost Data for Produced Water Disposal Into Disposal Wells

Water Demand

Available data in the literature indicate that in today's market, it may cost up to $20 million to drill a typical oil and gas well in Permian Basin, plus an additional 10% cost for water. This cost will include the required water for drilling, fracking, and disposal. The cost of water must be closely monitored throughout the producing life of the well.

Texas is the nation's number one oil and gas producer with more than 315,618 active oil and gas wells state-wide, according to oil and gas well proration schedules (as of June 30, 2015). Injection and disposal wells are also located throughout the state to both improve oil and gas recovery, and to safely dispose both the produced water, and hydraulic fracturing flow-back fluid from oil and gas produced by these wells. Texas has more than 54,700 permitted oil and gas injection and disposal wells with approximately 34,200 currently active as of July 2015. Of these 34,200 active injection and disposal wells, about 8,100 are wells used for disposal with the remainder (about 26,100) being injection wells[4] to enhance production.

In the oil and gas industry, water is used to enhance hydrocarbon production both by drilling and fracking. Drilling horizontal wells requires about 3-4 million gallons of water per well, and an average frack job requires about 5 million gallons of water. The usage of these large amounts of water causes a significant water stress on many Texas communities and on the drilling and production activities on the operating companies supplying water for oil and gas operations. The dilemma gets more intense when there is water shortage, or drought, in the Permian Basin region. These considerations are causing oil and gas producers to continually rethink their water strategies and develop new ways of reusing and recycling produced water.

Produced water is generally "processed" before use in fracking. First by treating to reduce the H**2**S content, and then metal ions (such as Fe). Finally, the addition of biocides, along with various types of proprietary treatments, complete the "treatment" of the water for hydraulic fracturing purposes.

The population increase listed in Table 4 below, and the current drought conditions in the region, it is evident that there will be a continuing need for non-potable water sources for the industrial (Oil and Gas) sector, to save the fresh water resources for human consumption and irrigation.

Year	2020	2030	2040	2050	2060	2070
Total	29.5	33.6	37.7	41.9	46.3	51.0

Table 4: 2016 Regional Water Plan - Population Projections for 2020-2070 State Summary (Millions)Texas Water Development Board January 2015

Water Forecast

Figure 2, below, shows the water shortage, demand, and supplies through 2070 for the State of Texas. With reference to this set of data, the potential shortage of water is increasing from 182,987 acre-ft/year in 2020 to 236,937 acre-ft/year by 2070, which is an increase of 23.7 % in 5 decades. The industry is also finding it difficult to obtain new sources of fresh water, which can lead to significant additional water stress in thisregion.

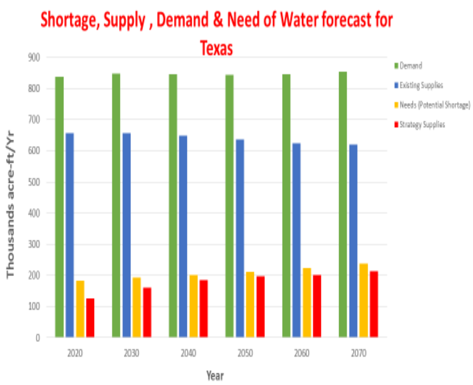


Figure 4: Shortage, Supply & Demand of Water Forecast for Texas

Texas Water Development Board January 2015

Having discussed the produced water supply, demand for water, and current water supply issues in the region, it is natural that the "produced water" from oil and gas operations be considered as a viable source of water for both the oil and gas industry, and for non-potable purposes.

Especially with the construction of a HTGR (High Temperature Gas Cooled Nuclear Reactor) in the region by which the produced water can be economically treated for beneficial use.

Below is a classification of water based on the Total Dissolved Solids (TDS) content. We will use these following definitions in this report.

Fresh water	0-999 mg/l TDS
Brackish water	1,000-9,999 mg/l TDS
Saline Water	10,000-35,000 mg/l TDS
Sea Water	35,000 mg/l and above

As of 2012, the State of Texas has 44 municipal brackish water and surface water desalination facilities[5]in operation. With the above-mentioned facts about the present condition of groundwater in Texas, it makes sense to be proactive and focus on taking strong steps to address these various issues so that an ample supply of good clean fresh water will be available for the future generations of Texas!

We are proposing that at least one gas-cooled (HTGR) nuclear power plant be constructed and operated immediately in Ector County, TX, with the purpose of utilizing its thermal energy to treat waters from both a) brackish aquifers, and b) oil and gas fields.

The proposed reactor will be the "first modular unit" which can be easily multiplied by the addition of additional reactor modules as the need may require. Further, the heat from the nuclear reactor(s) can be used for either treating produced water from O&G production, or the generation of electricity, and/or any other uses that require either process heat or electricity. As an example, the reactor/water treatment plant will also be capable of producing variable salinity (quality) water for both human consumption and/or industrial applications.

III. ENVIRONMENTAL PROBLEM: PRODUCED WATER VOLUMES AND DISPOSAL ACTIVITY IN PERMIAN BASIN

Induced Seismicity

One of the concerns related to oil and gas production in mid-continent U.S. in recent years has been the occurrences of induced seismic activities. Based on some reports, the induced seismicity is mainly due to produced water injection into the deep disposal wells - which is a normal practice in today's oil and gas industry. Figure 3 below shows trends in this part of the country since 1970's.[6]

"The earthquakes in the central and eastern United States from 1973 to April 2015 are shown in Figure 5 below. Two abrupt increases in the earthquake rate occurred in 2009 and 2013. The Red dots represent earthquakes that occurred between 2009 and April 2015, and blue dots represent earthquakes that occurred between 1973 and 2008. Red colour becomes brighter when there are more earthquakes in the area. The earthquake rate and distribution of earthquakes changed in 2009. Prior to 2009, earthquakes occurred across the United States. Beginning in 2009 the earthquakes have become more tightly clustered in a few areas (central Oklahoma, southern Kansas, central Arkansas, southeaster Colorado and northeaster New Mexico, and multiple parts of Texas)[6] that has significant oil and gas production."

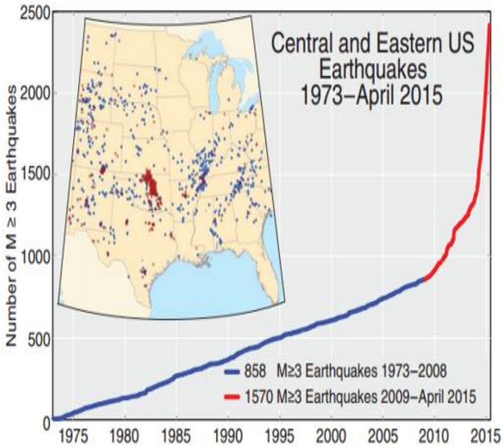


Figure 3: Seismic Activity in CEUS

Studies indicate that most of the seismic activities in Texas are primarily due to the injection of produced water from oil and gas operations into disposal wells. These injections typically cause a change in stress conditions on faults, which can cause failure in four ways:

- Increase of pore fluid pressure in a fault.
- Pore-elastic effect: The injected fluid increases the pressure inside the pore by compressing the fluid in the pore space causing deformation.
- Thermo-elastic deformation takes place due to the temperature difference between the injected fluid and the rock itself.
- Increased mass of the formation due to the injected fluids.

Therefore, the increased formation pressure plays a pivotal role in influencing induced earthquakes.

However, a more thorough investigation is necessary to examine the effects of the produced water injection into the wastewater disposal wells in the Permian Basin since deep injections are causing seismic disturbances in at least Oklahoma, Southern Kansas, Central Arkansas, southeaster Colorado, northeaster New Mexico, and multiple parts of Texas. It is prudent that this seismic issue in the Permian Basin be thoroughly examined since it has the potential to adversely affect the security of both the regional and national energy business.

Recent publications have indicated that operational parameters, such as the high rate of injection, are affecting the onset of earthquakes in places prone to seismic activities. For example, the data analysis has indicated that ahigh injection-rate salt-water disposal well is twice as likely as a low-rate well to be near seismic activity. The "high injection rate" wells are those with a 300,000 bbl/month rate, or greater[7].

Figure 6 below shows the existence of earthquakes (M≥0-3) associated with high rates of the injection of fluids in West Texas. The data reflects the time span from 1973 through 2014. Speculations indicates that other factors, such as the regional stress, fault size, its orientation, plus other geologic factors, may also influence these events.

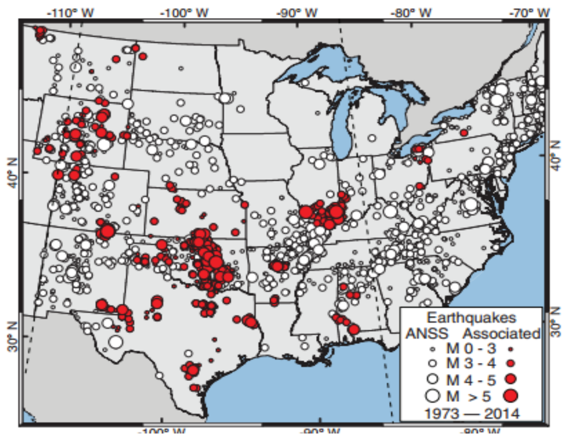


Figure 6: Earthquake Map of CEUS

Figure 7 below, is a map of the earthquakes in Permian Basin between 1973 and 2018 for the earthquake magnitudes between 2.5 and 6 Richter Scale. The cluster in northeast corner is near Snyder, which has considerable fracking activity, while the southwest cluster represents Pecos region with Monahan's' activity slightly to the north. To the very south, is the cluster that represents the West Texas region.

Figure 7: Seismic activity in Ector County and vicinity in the Permian Basin[9]

In summary, the proposed water treatment plant in this project will assist the oil and gas industry and region in several manners in the midterm horizon including;

- The security of energy flow and oil and gas industry
- Securing sources of treated water for industrial use and the community at large
- Mitigates/addresses the hazard of seismic activities for the public
- And finally, it is an environmentally sound step in minimizing the discharge to the environment

The plant also has the benefit of utilizing the process heat for other applications including the thermal desalination process, which will ultimately reduce the net operating cost for the nuclear power plant and assist the oil and gas industry by handling its produced water in a safer and more efficient manner. This ability to utilize the process heat will make a potential waste product a substantial profit factor.

Water Availability & Injection/Disposal in Permian Basin

One of the critical aspect of water treatment using the process heat from the small nuclear reactor, is the availability of the produced water from the oil and gas wells. Since this project is a commercial venture and the unit cost is volume sensitive, produced water data needs to be analyzed and water disposal be considered in determining where the facility will be ultimately located.

Based on reported water producton data, district 7C is basically flat for the water volumes during the 2008 through 2014, however, the produced water volumes are increasing steadily in District 8 (where Ector county and Midland county are located) for the same time period. This result indicates that the water production has increasing trend in this district

For the Injection and Disposal well utilization in Permian Basin from 2010 to 2014, it appears that, on average, majority of the counties are experiencing disposal pressure well utilization of fifty or more percent. It is apparent from the available data that there is an increasing trend for disposal from 2008 onward. District 8A has the highest disposal utilization in the permian.[10]

This trend shows that the disposed /injected volumes have increased in the Permian Basin steadily over time which can potentially lead to increased formation pressure and ultimately to seismic activities such as induced earthquakes.

IV. POTENTIAL SOLUTIONS

Water Treatment Technologies

There are several different technologies currently available for nuclear powered desalination plants. Reverse Osmosis is the most popular and generally the least expensive. However, since we have a virtually unlimited supply of heat, we will consider only the procedures that require process heat. The purpose of mentioning this process here is to compare and contrast the technologies cost wise and technology wise. The most common problem with the RO technology is the maintenance of the membranes used in the filtration process.

The two heat consuming processes are Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). The MED process is the least expensive of the two processes and has become widely accepted as a water treatment process in the industry. There are other technologies, such as Chemical processes, which are also available for water treatment purposes, but since there is huge amount of virtually "free process heat" available in this project, the focus of this paper will be on the heat related (thermal) processes and a brief comparison with the RO process. Below we will discuss briefly the three technologies mentioned above.

Reverse Osmosis (RO):

Reverse osmosis (See Figure 8 below) is a liquid purification process that uses a semipermeable membrane to remove dissolved, and undissolved, ions, molecules, and larger particles from a pure solvent, such as water. Both the dissolved, and undissolved, inorganic solids are removed from the solution by the hydrostatic pressure pushing the solvent (water in this case) through a semipermeable membrane while leaving both the dissolved solids and the solids behind. Figure 8 below is a schematic drawing of this process where water flows through the membrane while both the dissolved and undissolved salt particles remain at the entrance of the membrane [11].

Next, Figure 9 shows a more complex process where there is 1) "pre-filtration" prior to water passing through the membrane, coupled with 2) "post filtration," and accumulation tank and flow of purified water to the RO faucet. As mentioned above, this process does not require heat for desalination and it is generally a standalone project, especially in the Middle East and other locations where seawater is processed for human consumption[8]. However, we will contrast this process with the following two other processes namely, Multi-Stage Flash (MSF) and Multi-Effect

Distillation (MED) for distinguishing the applications and the costs related in these three processes. The latter two processes require heat/energy for desalination and are generally utilized where there exists an inexpensive source of energy (as heat) such be considered in our case where there is plenty of heat for heating water and steam generation where the vapour is condensed to create purified water. More details follow in the next sections.

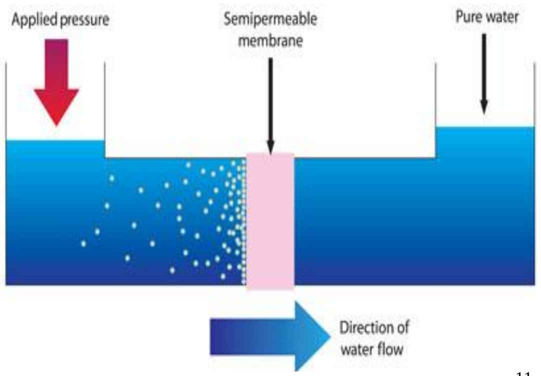


Figure 8: Schematic of Reverse Osmosis Process[11]

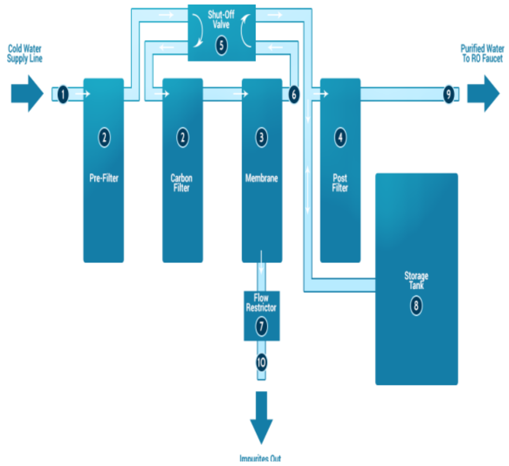


Figure 9: Schematic of Reverse Osmosis Process with Filtration[12]

The multistage-flash (MSF), MED (see below), and vapour-compression (VC) processes have led to the widespread use of distillation to desalinate seawater.[13]

Multi-Stage Flash (MSF):

TheMulti-Stage Flash process, shown in Figure 1**0** below, is another means for distilling seawater. The MSF process simply heats the saline water to temperatures of about 100-110 C and then "flashes" it (reducing the pressure in order to cause immediate boiling of the liquid) in stages while condensing the steam in each stage and collecting the distilled water. At the end of the process, the remaining brine is collected. In other words, several consecutive stages, called "evaporating chambers," are maintained at decreasing pressures, to enable the overheated fluid to flash and release heat in each stage while the produced vapour condenses into distilled water (fresh water). This process is illustrated in Figure 10[14].

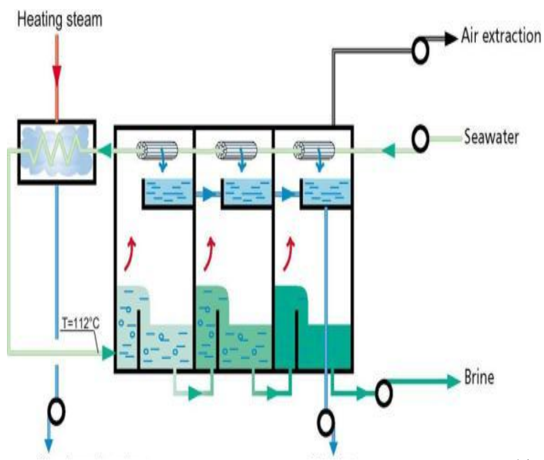


Figure 10: Multi-Stage Flash Process Schematic[14]

Multi-Effect Distillation (MED):

The MED process, shown in Figure 11 below, consists of several consecutive cells, called "effects," in which the flowing steam inside horizontal flow lines in each cell is cooled by means of make-up water flowing past the horizontal flow lines by means of gravity. The cooling effect of this process causes the steam to be condensed to fresh water that is then collected.

However, the "make up" seawater is only partially vaporized due to the latent heat at each cell, and is fed to the next cell as steam, due to the existence of a differential pressure caused by the lower temperature existing at each successive cell. This scheme is repeated and the condensate at each stage, and the distillate water at the final step, are collected. The remaining brine concentrate is also collected at the last cell.

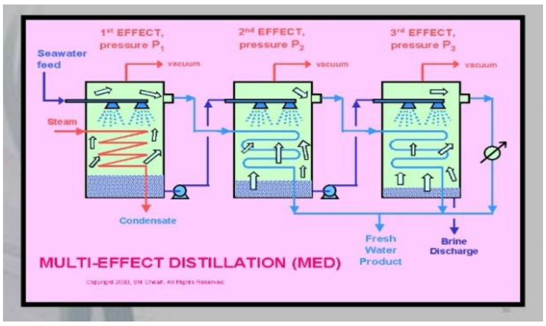


Figure 11: Multi-Effect Distillation Process Schematic[15]

b. New Technology Assessment on Water Quality (MYCELX)[16]

The RO processes briefly described above will remove the inorganic salts found in the produced waters in the oil and gas industry. However, the residual hydrocarbons, if any, must also be removed to make the water both potable for human consumption, and "clean enough" to get optimal benefit in the reuse in many oil and gas production processes such as directional drilling and the secondary recovery processes "water flooding" and "fracking."

The "MYCELX" technology is a treatment process for produced water that use a proprietary "staged" filtration process to remove hydrocarbons from water. The performance of their system as summarized on their web site is as follows:

- Inlet:100 ppm to 1,500 ppm oil in water, and 500 ppm of total suspended solids (TSS)
- Outlet:10 ppm for both oil in water and TSS

c. High Temperature Gas-Cooled Reactors

The conventional "water cooled" nuclear reactors that are in use today to generate electricity, the heat is generated by the fission of the Uranium U-235 isotope to fuel their boilers in order to make the steam that will generate the electricity, much like natural gas is used. That replaces the "coal" in coal-fired plants that also generate electricity. However, this process is corrosive and subject to component failure.

However, Unlike the other available designs of water-cooled nuclear reactors that generate our electricity which require human intervention to prevent potentially catastrophic operating conditions, the helium gas-cooled reactor is classified as "intrinsically safe" due the unique design of the fuel. The most dangerous part of any nuclear reactor is the Uranium fuel that is "enriched" in "fissionable" isotope U-235. The reactor operation is based on the simple concept that normal operation takes place when the coolant gas, He, is able to remove enough heat caused by the fission process such that the U-235 does not overheat.

Currently, there are preliminary plans for constructing at least one 150 MW $(th)_{)}$ nuclear reactor in Ector County, TX, to treat brackish and/or the so-called "produced" water from oil and gas production to "drinking water" standards. This reactor will be a commercial High-Temperature Gas-Cooled Reactor that will operate at temperatures as high as 1700 F and be "intrinsically safe (meaning that it will stop operating, by the laws of Physics, rather than require a human operator to make the decision. This enormous amount of process heat will treat the so-called "produced water," created during the production operations from oil and gas wells, to drinking quality water standards via a process similar to those discussed above. The capacity of this plant will depend on the quality of the produced water.

The fuel is encased in graphite "micro-spheres" that are ~1mm in diameter. These micro-spheres are constructed such that if they start to overheat, they will automatically "swell" swell in size just enough to cause the fission to cease, which is contained in a unique "micro-pellet" primarily to the physics designed into the fuel/pellet construction. that forces the reactor to be automatically shut down by the laws of Physics (the fuel particles expand just enough for the "fission" process to be automatically terminated) if the fuel gets too hot. Another unique feature of this reactor type is its ability to seamlessly switch from generating electricity to utilizing the process heat with a simple electrical switch.

The reactor is also capable of operating continuously for ~75 years without stopping for refuelling, as it is automatically "self-refuelled." The reactor fuel is contained in hundreds of graphite spheres that are each about the size of a "tennis ball" in the reactor core. These graphite spheres contain the reactor fuel and are dropped into the top of the core and ~~are~~ driven to the bottom of the reactor core by gravitational force. Once they reach bottom of the reactor core they "fall out" of the core and are automatically moved to the "spent-fuel" facility for disposal. This is like the situation found in the old "penny gum-ball" dispensers 50 years or so ago. In those dispensers, you would insert a penny and one gumball, and only one gumball would be dispensed. After it was dispensed, the balls inside the gumball would automatically rearrange their configuration to make room for an additional "gum ball. There are openings at both the top and bottom of the core that is the size of one of these pebbles.

When a "fuel ball" is used up (or, spent) it , This is due to the unique reactor design and dynamic system of fuel change which does not require the reactor operation to be shut down for refuelling.

The benefits of utilizing this amount of heat for water treatment and diverting the treated water for oil and gas industry applications and other uses will be in the interest of the oil and gas industry, irrigation, and the community at large. The question to be addressed is the gathering of the produced water via trucking and or piping to the proposed treatment plant. It is outmost importance that the process is economical. This aspect will be discussed in product cost section below.

In summary, this paper is proposing that the process heat from the HTGR be used to treat produced water from oil and gas fields/brackish water. This process not only benefits the community and mitigates water shortage in this region for oil and gas industry and the community at large, but also the marketing and sale of such heat will also decrease the net operating cost of the nuclear reactor.

V. WATER QUALITY & COST OF WATER PRODUCTION

IAEA Data

Due to fresh water shortage in Texas and specifically in West Texas, the oil producing companies are recycling, reusing and utilizing brackish water for hydraulic fracturing purpose. This report is an attempt to promote the idea of using produced water from hydrocarbon production in the Ector county. The feed water (produced water/brackish water) can be processed by thermal process for use in oil and gas industry, human consumption, and others alike.

Since produced water has contaminants and inherently some grease and oil in it, it is our understanding that an RO-Thermal process will serve the treatment process better.

One of the main concerns in this project is cost of treating produced water. Equally important is the possibility of the proposed treatment facility to process produced water to potable water quality. The ultimate product can be used for industrial, irrigation, and civilian purposes. The brackish water will be processed for potable water use.

Process heat from the nuclear reactor will facilitate treatment process leading toward production of high quality water. Globally, nuclear desalination projects are attractive investments to meet human water demand. Since the process heat is primarily a by-product of the reactor operation, the use of this enormous amount of heat (up to 1700 F) for water treatment will be very cost-effective process. It is important to note that the sale and revenue from process heat will be a means of reducing net operating cost of the plant.

Recently some of the oil and gas operators have embarked on recycling and reuse of wastewater from hydraulic fracturing operation. Excluding outlays for its home-grown recycling system, Apache has indicated that it costs the corporation 29 cents a barrel to treat flow-back water [17]. Recent studies have shown that fresh water sources can be impacted by drilling and hydraulic fracturing activities. As such, even if recycling and reuse of hydraulic fracturing flow-back and produced wastewaters is technically and economically feasible and supported by industry and the public, the ability of operators to do so can be influenced by state and local regulatory and legal aspects.[5] Moreover, the contribution of the volume of recycling and reusing is about 6-10% of the water required for a frac job. (Chesapeake Energy Report). It is essential that a remedy for water shortage and stress be sought since the region is in dire need of water for industrial and other applications. The data available in Table 6 indicate that a hybrid process will cost only 17.5 Cents per barrel for water with quality of 125-175 ppm. Our current understanding is that water treatment process will result in water with drinking quality with the price range of $0.20-$0.60 a barrel.[18]

It is worth noting that approximately 70% of water used in hydraulic fracturing in Midland basin is freshwater. Generally, majority of water in the basin is suitable for use with slick water hydraulic fracturing.[19]

It is also worth noting that IAEA studies have indicated that nuclear option will be competitive if natural gas prices remain above 150 $/toe ($21 /bbl of Oil, / $3.53/ MCF of Natural Gas) and discount rates are below 10%. (IAEA p78)[20]. Currently, the average price for an MCF of natural gas in the U.S., for the period of 2009-2016, is in the range of $3.65-$3.80.[21]

Table 5 below shows the amount of heat/specific energy used for each process. Multi-Stage Flash (MSF) has the highest energy requirement followed by Multi-Effect Distillation (MED), and Reverse Osmosis (RO) process. However, as indicated in Table 6, RO process has lower product quality (PPM) of the desalination process of saline water and MSF has the highest.

A hybrid process is somewhere in between. As indicated in Table 5 and Table 6, thermal processes require more energy and produce better (low salinity) water. For oil and gas industry it is possible that treated water be blended with lower quality water (i.e. higher salinity) for hydraulic fracturing if necessary

.

Table 5: Specific Energy Consumption of Desalination Plants

Process	Specific Heat Consumption	Specific Electricity Consumption
	KW(th).h/m^3	KW(e).h/m^3

MSF	100	3
MED	50	2-3
RO	0	4.5

Table 6 lists the price of desalinated water by using the RO, MSF and a Hybrid process. The price reported per barrel/m^3 (6.29 bbl /cubic meter), of water is $0.15/$0.95 for RO process while for MSF it is $0.188/$1.18. The hybrid process which has product quality of 125-175 ppm has water production cost of $0.175/$1.10 respectively.

Table 6: Costs of Different Quality Waters in the Hybrid System

Type of Desalination Process	Product Quality (ppm)	Water Cost ($/bbl)	Water Cost ($/m^3)
RO	350-500	0.151	0.95
MSF	10	0.188	1.18
Hybrid (MSF & RO)	125-175	0.175	1.10

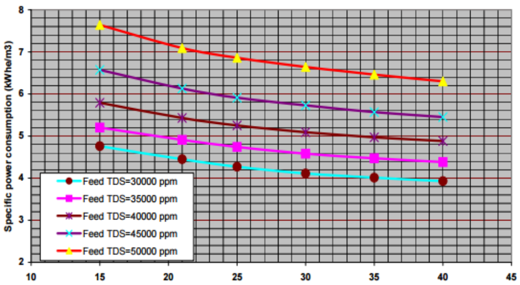
Below in Table 7, several characteristics of MSF and MED technologies have been compared. The MED process is less costly and less energy intensive.

Table 7: Comparison of MSF & MED Processes

Item	MSF	MED
Number of modules	5	12
Capacity/module (**m^3/day**)	68 130	28 930
Vapour flow rate (**t/h**)	1860	1860
Vapour pressure (**bar**)	1,5	5
Thermal power consumption (**MW(th)**)	42	17
Land surface area (**m^2**)	127 X 385	110 X 250
Turn key cost (**M$**)	375	265

Figure 12 shows the power consumption as a function of Feed temperature for thermal process with differing TDS values. The graph indicates that as the Feed TDS increases, the specific power consumption also increases. The required heat for the fluid

Figure 12: The Power Consumption Vs. Feed Temperature for Different TDS[20]



With higher Total Dissolved Solids (TDS) content is higher since it will require more incremental heat to heat and vaporize the higher content TDS fluid.

The next logical question would be the costs related to the nuclear powered water treatment facility and the factors influencing it. Based on IAEA report the costs are strongly influenced by interest/discount rates, the total plant availability, the power costs, the specific water plant base costs etc. In general, it can be stated that RO costs would be in the range of $.079 /bbl to $0.143 /bbl (0.50 to 0.90 $/m3). Desalination costs from thermal systems such as the MED would be slightly higher, being in the range of $0.095/bbl to $0.153/bbl (0.60 to 0.96 $/m3).(Refer to Table 8).

Table 8: Process Type & Corresponding Unit Water Cost

Process Type	Cost ($/bbl)	Cost ($/m^3)
RO	**0.079 – 0.143**	**0.5 – 0.9**

MED	**0.095 – 0.153**	**0.6 – 0.96**

It should be recalled that the product water salinity by thermal desalination plants is much lower (about 30 ppm) as compared to 300 to 500 ppm for an RO process (78 plants). The real choice of one over the other would thus depend on the application implemented (i.e. depending upon the specific industrial, agricultural requirement/ human consumption).

Based on the study completed by IAEA regarding the nuclear desalination projects the report indicates that this process can readily be considered as a competitive alternative to conventional fossil fuel powered cogeneration plants. In addition to providing a range of water products of various qualities and operational flexibility, the hybrid RO/LT-MED (Low Temperature) MED plant option offers water costs that are very close to those of the stand-alone RO seawater plant[20]. (IAEA report)

Following is a demonstration of a typical desalination plant in Pakistan. The figures and the data are specific to this nuclear power desalination plant. However, similar data is available for other countries which have embarked on a similar power plants internationally. The purpose of this set of data and the corresponding figures are to show produced water cost sensitivity to certain parameters of economic importance. Figure 13 shows Water cost sensitivity to interest rate variation. As the interest rate increases so does the water cost.

Figure 13: Water Cost VS. Interest Rate [20]

Disposal

of brine (

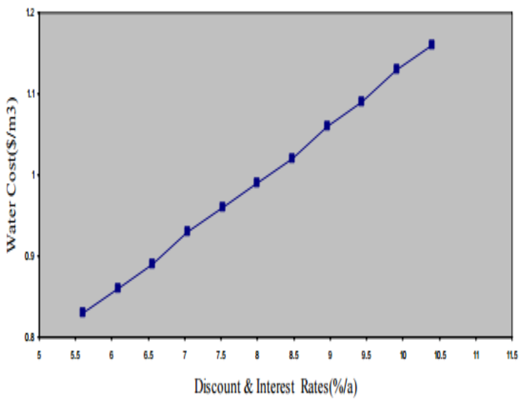
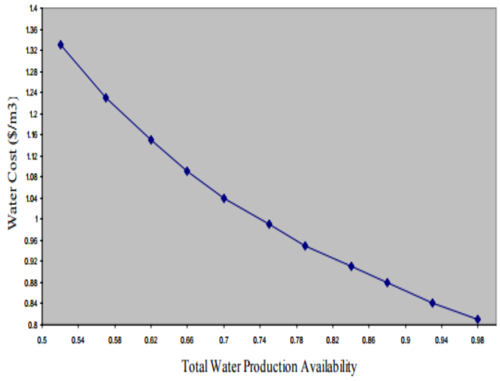


Figure 14: Water Cost Vs. Total Water Production Availability[20]



a. Local Data

The section above covered the desalination cost and the parameters influencing it at an international level. In this section we will discuss costs inherent in handling water for oil and gas operators or producers in the Permian Basin.

Below is the list of costs related to water purchase, treatment, and disposal locally in Permian Basin.

Freshwater purchase (average cost)
$0.50 /bbl Plus $1.10 /bbl for hauling[22]

Trucking & disposing Water (Barnhart region)
$2.0 - $2.50 /bbl[23]

Other estimate
$3.0 /bbl

Trucking from location to disposal site
$50/1000 gal [24]

Trucking is generally
$88/hr[25]$60 – 90 /hr. [25]

Cost of disposal well
$500,000 +$1/1000 gallons[24]

Treatment cost are as follows Recycling (for hydraulic fracturing) – Apache Data $0.29 /bbl[17]

Oil field produced water Desalination Cost
$4.0 - $8.0/bbl [24]

Salttech Technology (by STW) Oil water desalination $1.50 - $2.0/bbl[23]

Salttech Technology (by STW) Purify brackish
$.14 - $.15/bbl [23]

Since brackish water desalination in Texas is also being considered, the following cost estimates are included.

Table 9: Total Water Production Cost in Texas [26]

Capital Cost ($/gal)	Operations & Maintenance ($/1000gal)	Total Water Production Cost ($/1000 gal) OR ($/bbl)
2.03 – 3.91	**0.53-1.16**	**1.09-2.40 OR (.046-.101)**

The transportation or hauling cost of water to the treatment plant can vary by the means utilized. It can either be transported by trucks or by a piping system. Truck hauling cost is about $0.09/bbl/mile or $1.50/bbl minimum. However, this cost can be mitigated to $0.02/bbl/mile when pipeline transport is used [27].

Below is cost data for several alternatives, such as deep injection, chemical treatment, use of mobile treatment unit to site, disposal and the trucking costs by these alternatives.

Table 10: Cost of Different Processes

Process	**Cost ($/gal)**	**Cost ($/bbl)**
Deep Injection	0.11	4.62
Trucking to water treatment site	0.075	3.15
Chemical treatment	0.20	8.40
Transportation of mobile treatment unit to site	0.007-0.012	0.30 – 0.50
Disposal	.0120	0.50
Trucking to water disposal site	0.024	1.0

One alternative to the above-mentioned disposal options is to treat frac fluid for reuse. This market can grow to a $9 billion industry by 2020. Global water intelligence predicts that market for produced water treatment will rise to $2.9 billion in 2025 from $693 million now [28].

Recycling of fracking waste is somewhat worrisome since the residual waste coming out of the process could be toxic and it is not governed under waste rules. Since oil and gas industry is exempt from the federal law that governs hazardous waste there needs to be legislation around this issue

VI. ANALYSIS

This section focuses on the analysis and discussion of the proposed water treatment as a solution to the fresh water shortage/stress with a profitable business model. It is the intention of this paper to put forward a solution which not only is a sound business plan, but also addresses the long-term public well-being in terms of fresh water resources, safety, and the environment protection.

The inherent theme of this study is that energy production security can be enhanced by seeking assistance from mother nature while addressing the pressing issue of fresh water scarcity in the Permian Basin. This is a solution in the context of water-energy nexus.

Construction of a 1.5 billion-dollar Helium Gas Cooled Nuclear Power Plant with a water treatment facility is proposed. The plant will generate 150 MW $_{(th)}$ of energy that will be in the form of electricity “process heat”, which will be utilized to treat both produced water from oil and gas fields in Ector county and brackish water.

The essence of this project is coupling of nuclear and the oil and gas industries together, bearing in mind that both entities are energy industries focused on different aspects of the public needs. The combining of the two industries’ technologies will lead to a solution of a dire problem in the freshwater resources.

A sound business model which addresses the needs of the oil and gas industry and the well-being of the public water supplies with sound economic plan, will be a solution for the projected long-term “water scarcity” in the Permian Basin. This business model is capable of delivering high quality water (drinking water quality) at an attractive price for a long-term horizon. The proposed plan addresses the “bottom line” of the entities involved, but also focuses on the water shortage/stress in the US and mitigates the environmental risks impacts. In short, it is a Win-Win situation for all the parties involved.

Applications for water treatment plant

At least one of the proposed water treatment plants to be erected in Ector county, will have multiple functions, in order to meet the needs of the region at large. Since the focus of this paper is on the applications of water treatment in Ector county, it is natural that industrial water needs and community consumption both need to be addressed and discussed.

The Permian basin is home to significant oil and gas resources and production for the nation where enhanced oil production processes such as hydraulic fracturing and horizontal drilling, are widely implemented. Hydraulic fracturing utilizes an average of 5 million gallons of water per well and horizontal drilling uses about 3 to 4 million gallons of water per well. This considerable amount of water is a combination of fresh water and recycled water from flow back or waste water stream. For a region that is suffering from water stress, there is justified concerns for the amount of water that is going to be needed for the number of wells which are planned to be drilled and or thousands that are going to be drilled in the future for hydrocarbon production. In other words, the present and future development plans require sub structural planning for water used in oil and gas well development. Simply stated, the oil and gas industry is dependent on water!

Another important aspect is the dependence of human survival on fresh water. Mankind needs freshwater for its daily survival. Continuation of life on the Earth depends on water and so does the quality and standard of living.

The question that is being addressed in this paper is whether or not we can strike a balance between sustenance of life and standard of living? Can we arrange the activities such that both conditions can be met? Life without water cannot continue and life in stone age is not practical. After all, the progress that has been made to create the standard of living which we all enjoy now, cannot be ignored.

Moreover, the current practice on recycling and produced water disposal will most likely adversely affect the water resources in the region.

This paper and the project intend to address two aspects of life dependency on water plus the environmental impacts that current practices may have concerning this issue.

This paper is proposing the following:

(1) A small nuclear power plant that utilizes new technologies, will be constructed in Ector county, and the process heat (1700 F) from this facility will be utilized for treatment of water and waste water.
(2) By constructing a water treatment plant next to a nuclear power plant, it is possible to treat produced water from oil and gas fields for industrial applications and brackish water for human consumption respectively.
(3) In this scheme of operation, the oil and gas industry will be able to utilize this treated produced water from the oil and gas fields for hydraulic fracturing, horizontal drilling, and destruction of all kind of wastes, including hazardous waste.
(4) The public and the community at large can also benefit from treatment of brackish water to potable water and or agricultural uses.
(5) The end result will be increase of the fresh water for life sustenance and energy flow in the region and in the United States.
(6) The environment will be protected from the injection of minimally treated frac fluid and the flow back water recycling.
(7) It is a win-win outcome for the oil and gas industry, the public, and the regulators.

b. Economic Incentives

One of the main concerns in this project is the economic aspects of treating water and the product (the treated water) price. The 1.5-2-billion-dollar project, will include construction of a (with 1 acre block footprint) small150 MW $_{TH}$ Helium Gas Cooled Nuclear Plant with an onsite water treatment plant. Based on a preliminary calculation, for a 25 $MW_{(th)}$ power plant, 46,500 bbl/D of water can be treated utilizing Multi-Effect Distillation (MED) process.

The DOE is estimating that treated water with drinking water quality will cost as indicated in the Table 11 below;

	$/42 gal BBL	**$/gal**
Lowest Price	$0.16	$0.004
Highest Price	$0.60	$0.014

Table 14: Price Range for Treated Water[29]

The price for treated water ranges between 16 to 60 Cents per barrel. The treated water source will be either brackish water leading to drinking water stream or produced water leading to water for industrial applications.

Since the oil and gas industry is currently utilizing brackish water for fracking, which is more saline than fresh water, it is therefore possible that the water products from the plant be blended with other types of water (i.e. brackish water) for industrial applications. The high-end product, namely, drinking water can be utilized for human consumption and be in the market as a commodity.

The current market value for "fresh water" in this region by independent oil and gas producers is about 50 cents per barrel plus the hauling costs. This cost is anywhere from 90 cents per barrel per mile to as high as $1.50 per barrel per mile. As an example, the volumes offered by producers' range between a few thousand barrels to one hundred thousand barrels in Odessa, Texas[22].

C. Environmental Concerns

In this region, water shortage and water stress concerns have been increasing since the 1940's. The oil and gas industry has been seeking solutions to remedy this problem in its practice. The priority has been to minimize use of fresh water for fracking applications. To accomplish this brackish water has been utilized. Another measure has been to recycle the waste water/flow back water. These efforts have been underway to cut down use of fresh water and thus save it for potable water use. However, the contribution of these approaches in the big picture is insignificant. A more comprehensive, effective, and long-lasting approach needs to be sought and substituted for the current practice.

We believe that the current minimal treatment of the flow back water, which is being recycled for further applications, is not a safeguard to the environment and the water resources. In other words, more effective means, such as those we are discussing, should be implemented to better protect the environment.

A more viable approach is being proposed; water may be outsourced from a rigorous treatment of the produced water from oil and gas fields. Our proposed treatment plant can produce quality water for industrial application with attractive economic costs. This solution makes economic sense while protecting the environment and thus preserving the safety and health of the community at large.

To ensure the integrity of the environment and its protection, it is necessary that state regulators be involved more effectively. This project guarantees that the flow of energy to the energy markets is protected, while the needs and the wellbeing of the community are preserved, and the existing environmental issues are addresses.

Sources of Economic Data

This paper has considered three main sources of data for cost/benefit analysis.

(1) International/National based data from IAEA
(2) Locally obtained/local-specific cost data
(3) Department of Energy (DOE) analysis at the INL (Idaho National Laboratories).

The international data has the advantage of sourcing several countries' experience on constructing multi-million-dollar nuclear water desalination projects. Another strength of the data is comparison of different technology costs and or the hybrid treatment systems. It is important to note that since these cost data are at economies of scale, it is prudent that the treatment facility be operated at high volume/capacity to provide most efficient and cost-effective water treatment operation. This approach will benefit oil and gas industry and the community at large. Therefore, produced water gathering, hauling/transportation via trucking or piping, needs special attention since economically speaking, one of the major costs is water hauling expense. It is well established fact that water hauling is an added high expense that could be reduced by means of piping, though this undertaking requires an up-front capital investment. An economic analysis needs to be performed for cost-benefit analysis.

The data obtained from IAEA indicate that cost of a unit production of water will be about 15.7 Cents per bbl. The data at the national level indicate unit production water cost of about 16 Cents per bbl. The difference between the two cost estimates is insignificant. As an aside, the nuclear plants can be designed from generating process heat for waste water treatment, to generating electricity with the simple 'flip of a switch'.

The local cost data gathered, however, has higher degree of uncertainty. There is therefore, more uncertainty to build a cost estimate model with the local data since this project is the first of its kind in the US. Since it is yet to be determined if the produced water will be hauled to the location/facility or there will a piping system to collect the produced water, this by itself will have a significant impact on the finished product cost. As a result, the IAEA data is more transparent than the locally obtained cost data now. Currently, cost of 20 – 60 Cents per bbl. for water of drinking quality is the price range in this project.

The last set of cost data is the Sourcewater cost database available online. The general "fresh water" cost data indicate that it costs about 50 cents/bbl. to purchase fresh water (at the field/location), however, there will be an added expense of about one dollar a barrel for hauling water to the desired location.

It seems that for water treatment, it will be economical to pipe water to the treatment facility rather than hauling/trucking it to the facility. However, piping will require an initial capital cost of constructing a piping system plus designating collection centres for produced water gathering for further transferring to the treatment facility. This plan has potential of reducing water hauling cost.

It is worth noting that produced water will be available for at least as long as there is hydrocarbon production. Depending on the industry needs, water can best fit for applications such as drilling and hydraulic fracturing. The treated produced water can be used as a high-quality water or as a hybrid mixed with saline water. Brackish water can be treated to a drinking water quality,

A point of uncertainty for the use of brackish water is its suitability and application in hydraulic fracturing. Based on some literature data, brackish water might not be readily advisable for use in hydraulic fracturing when cross-linked gel systems are used [23]. Therefore, one must consider the limitations of brackish water for its application for industrial use. Fresh water/treated water can always be used for the applications. Thus, the limiting factor will be the cost of treated water from the plant.

There will be an inherent competition between the use of treated produced water and brackish water by the oil and gas industry. The economics will determine which process to adopt. Our preliminary results indicate that treated waste water not only is a better-quality water and better suited for industrial use, but also is more cost effective. The lowest reported water treatment plan is use of recycled water with the cost of $0.29/bbl. for the waste water by Apache, whereas our proposed water treatment plan has the potential for lower costs and substantially better-quality water.

The use of treated wastewater is less-riskier to the public health and the community while it is more cost effective. In-fact this approach is taking advantage of the natural flow of the order in nature. Therefore, the feasibility of this project is called for at least in the Permian Basin if not in the US.

Based on the IAEA data[20] (Pakistan Case) the average cost of producing desalinated water from a desalination plant at 8% discount rate is about $0.157 /bbl. ($0.99/m^3). Our process requires that the feed water is either sea water or at best a brackish water (lower TDS).

For the produced water treatment process, the treatment will require to eliminate H2S, addition of Biocides for bacteria, solids and oil and grease removal.

The disposal of the treated produced water into fresh water formations requires that an environmental impact assessment be conducted since it has potential to influence oil and gas industry and consequently security of the energy flow. Coupled to this concern is the hazard associated with the seismic activity and consequent public health risks.

Finally, the treated water can be of interest to the municipalities and for agricultural/irrigation applications. Since the area is suffering from lack of fresh water and is under water stress, it is of utmost importance to discuss the issue and find ways to transfer the benefits of treated water to the community.

VII. CONCLUSIONS

Following conclusions may be drawn from the section above:

(1) The privately financed 1.5 – 2-billion-dollar project with electricity generation and treatment processes is a beneficial project for the region and a model project for the US and the world.
(2) The lowest and highest price for the treated water is $0.16 per barrel and $0.60 per barrel.
(3) The water treatment plant will benefit the oil and gas industry by providing treated “fresh” water from the produced water stream for fracking and horizontal drilling and agricultural purposes.
(4) The water treatment plant will also treat brackish water which will meet the drinking water needs of the community at large.
(5) The successful treatment of water by this project will protect the environment. It has the potential to end the partial treatment of flow back water which is used for recycling and reusing, which is ultimately injected to the disposal wells?
(6) This project is a win-win situation for both the oil and gas industry and the public safety.
(7) The potential of this project will assist the regulators in protecting the environment more effectively.
(8) The application of process heat for the treatment purposes is a means of reducing reactor operating cost.
(9) The proposed treated water costs are economically attractive.
(10) Finally, this project and alike have the potential to diversify the economy in this region

RECOMMENDATIONS

(1) More cost estimation of pre-treatment of the process needs to be completed.
(2) Detailed work is needed to complete the specifics of the treatment process.

(3) Production data and specifics be included for the location of the plant.
(4) Injection data of the produced water be investigated.

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Hossein Hosseini "Produced Water Treatment Utili
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James Wright BIO

Dr. Wright is the former Director of the HT3R Program at the University of Texas of the Permian Basin. He received his PhD at the US Atomic Energy's Ames Laboratory at Iowa State University. His work history includes being a Research Scientist at Battelle's Pacific Northwest Laboratory, a Staff Member and Program Manager at Los Alamos Scientific Laboratory, owner of an international energy consulting company, and the Director of the HT3R Office at the University of Texas of the Permian Basin (UTPB). In addition to authoring several classified papers, he also developed an analytical process and methodology to use as a tool in "risk analysis," as described in his book titled "Monte Carl Risk Analysis and Due Diligence of New Business Ventures." He also managed the creation of the Pre-Conceptual Design of the "High-Temperature Teaching and Test Reactor" to be placed in the Permian Basin of west Texas.