SINGLE AND DUAL PURPOSE NUCLEAR DESALINATION

© M. Ragheb
3/26/2013

INTRODUCTION

We discuss the use of single purpose water production and dual purpose electricity and water production plants. An expression for the combined water and electrical production is derived. The total cycle efficiency appears as a sum of the electrical production efficiency and the water production efficiency weighted by the ratio of the absolute heat addition temperature to the water cycle to the absolute heat addition temperature to the electrical cycle. The underlying thermodynamic considerations reveal that the water production and electricity production processes are competitive rather than complementary processes from the overall cycle's efficiency perspective. Improving the water production process would be at the expense of the electrical production process, and vice versa. It follows that a dual purpose plant rejecting heat from the electrical production process to a water plant would not necessarily be more efficient than a single purpose water production plant. This suggests the need for a close consideration of the needed water electricity mix for such plants at the design stage to accommodate different situations.

UNSUSTAINABLE FRESH WATER USE

The fresh water industry is the third largest industry in the world valued at $\$300x10^9$ per year by the UK Trade and Investment Ministry.

According to Fred Pearce, New Scientist news editor and author of: "When The Rivers Run Dry,": "A typical meat-eating, milk-guzzling Westerner consumes as much as a hundred times their own weight in water every day." That is because it takes 1,000 tonnes of water to grow 1 tonne of wheat, 2,000-5,000 liters of water to grow one kilogram of rice, 11,000 liters to grow the feed for a cow for a ¼ pound hamburger, 50 cups of water for a teaspoon of sugar and 140 liters of water to produce one cup of coffee.

The world today grows 2 times as much food as it did in the 1960s but uses 3 times as much fresh water to grow it. Two-thirds of all the water taken from the environment is used in crops irrigation. Fred Pearce suggests: "This is massively unsustainable, and has led many people to conclude that the apocalypse wasn't averted, only postponed."

VIRTUAL WATER

The overuse of fresh water does not just apply to food production, but also to industrial production. Every T-shirt takes 25 bathtubs of water to produce and every small automobile uses 450,000 liters.

By consuming imported goods from other countries, people are exploliting rivers of fresh water from across the world. Water used for growing food and making products is designated as “virtual water.” Tony Allan of the School of Oriental and African Studies in London, invented the term “virtual water.”

The global virtual water trade is estimated at around 1,000 cubic kilometers a year, or 20 Nile Rivers. Two thirds of it is used is in crop production, 1/4 in meat and dairy products, and 1/10 in industrial production.

The largest net exporter of virtual water is the USA, which exports in grain and meat around 1/3 of all the water it takes from the environment. Canada, Australia, Argentina and Thailand are similarly net exporters.

Importers of virtual water, like Japan and the European Union (EU), are not short of water. For others like Iran, Egypt and Algeria, it is a vital import. Jordan imports 80-90 percent of its water in the form of food.

GLOBAL WATER SHORTAGE

According to Juliette Jowit of The Observer: “Rainy regions like the British Isles have not escaped a worldwide drought phenomenon.” The city of London's long term average rainfall has dropped below that of the cities of Istanbul, Dallas and Nairobi.” The UK government considered proposals to introduce drought orders banning “non-essential” use of water.

Australia suffers from a severe drought as well. India's water table is at an all-time low and dropping fast. In some areas, it has fallen from 20 to 285 feet below ground level in the last decade. China is suffering from annual droughts, with the city of Beijing besieged by sand storms blowing down from the ever expanding Gobi Desert.

The southwestern USA is struggling to find enough water for its growing population. California and Nevada are being particularly hard hit, and the shortage is getting worse.

Rivers are running dry across the world, from the Rio Grande in Texas to India and Northern Nigeria. The Aral Sea in central Asia, where a thriving fishing industry died as the rivers inflow into the sea was drained to feed cotton farms, has shrunk in size and the population on its shore is poisoned by dust storms of salt and residual agricultural chemicals.

Governments who concentrate on building dams and draining subterranean aquifers need to look for alternatives. Crops can be grown with a quarter of the water currently used using methods such as drip irrigation and the lining of waterways to avert water seepage. Most people do not pay an economic price for water because government subsidies keep prices artificially low. Without a price incentive, they would not cut back on their usage.

The world's water pipes are crumbling where much of the water supply leaks into the ground before reaching the consumers necessitating repair and replacement.

FRESH WATER TRADE

There are countries that have an over-abundance of water with opportunities for sale to other countries. Canada has the same amount of water as China, but just 2.3 percent of its population. Brazil has far less need of its water than many of its neighbors. As the value of water rises, countries like these could consider exporting their spare reserves to those more in need and willing to pay. Pipelines are springing up, connecting states and countries. Tankers may in the future transport water across the sea as often as they do petroleum. The shaping and tugging icebergs from Antarctica to desert areas of the Middle East has been considered. Fresh water is on the move across the globe.

Turkey exports water to Israel and Cyprus in large floating balloons that can hold up to five million gallons of water. Singapore buys 10 percent of its water from private sector suppliers who have built desaliniation plants in order to reduce its reliance on Malaysia. Companies in Scandinavia are investigating the ways in which they can profit from their watery landscapes, such as one company that is considering the shipping of the equivalent of 1,000 Olympic swimming pools of water to Iran per day.

THE DESALINATION ALTERNATIVE

In Southern Europe and other arid regions of the world, alternatives, such as desalination, are set for sustainable growth. Southern Spain's Andalucía, one of Europe's most arid regions, is also the continent's most productive agricultural area. Intensive irrigation has seriously depleted its fresh water resources. The city of Almeria collects and recycles all of its water, using it for agriculture. The newly created Programa Agua will supply desalinization facilities all along the Mediterranean coast.

This is an alternative that has long been considered too expensive, but that state of affairs is changing. Large amounts of power are needed to drive the pumps and the unit costs are coming down.

The traditional players have been in the Middle East, such as Saudi Arabia, Kuwait, Dubai, and island communities. Malta and the Canaries Islands have been using desalination for 4-5 decades because it has been their only source of water. Big cities are beginning to consider it seriously. The city of Perth in Australia has given the go-ahead for a large desalination plant.

New water quality standards are being put in place in countries such as China and India, which will drive major new investments in fresh water production, infrastructure, treatment and purification.

JUSTIFICATION

Single purpose water production plants and dual purpose electrical and fresh water production plants using nuclear, wind, solar or fossil sources could augment the available water supplies in arid regions of the world adjacent to sea shores, whenever long distance conveyance of water is not possible, for engineering, economical, or political reasons. Fresh water is increasingly conceived as the most precious global resource for this century, ahead of petroleum, minerals and forests.

As the world’s population grows, the strain on the constant fresh water supply is increasing creating sources of conflict that can be avoided through supply augmentation, in addition to reuse and conservation.

The need for fresh water is accentuated by the increasing salinization problems in irrigated regions of the world, turning fertile agricultural land into salty deserts. The produced electricity would be used for the pumping of drainage water and reducing the height of the water table below the critical depth of two meters, reducing the salinity level and providing increased water development.

Along sea shores hydrogen can be produced through high temperature water electrolysis to be pumped inland providing electricity from fuel cells and concurrently fresh water from the process.

In the arid regions of the world, electrical production plants can be used inland for the treatment of brackish underground water supplies using electro dialysis or reverse osmosis. Along sea shores, distillation methods can be used for the production of large amounts of fresh water to be used locally or to be pumped inland.

Under consideration, dual purpose plants are favored on the tacit assumption that it may be advantageous to be use the heat rejection from the electrical production process as a source of lower grade heat to the desalination process. After all, the desalination process requires low temperature operation to avoid precipitation of salts at high temperature leading to fouling and scaling of the heat transfer surfaces, as well as clogging of the piping.

The dual electricity and fresh water production approach faces the hurdle of producing large blocks of electrical power to relatively small grids that could not accommodate them, and to locations where fresh water supplies are needed more urgently than electrical supplies. The use of agro industrial complexes has been suggested as a means of using the large blocks of electrical power produced by the dual purpose plants. We consider here the alternative of single purpose plants producing primarily fresh water with a smaller electrical component satisfying the plant and local needs.

THERMODYNAMIC CONSIDERATIONS

We consider the absolute temperature T = 273 + ^{o}C against entropy S diagram modeling a heat addition Q_A to an electrical production model producing electrical energy in the amount:

$$W_E = (T_1 - T_2)\,\Delta S \qquad (1)$$

T_1 is the heat addition temperature,

where: T_2 is the heat rejection temperature to the water cycle,

ΔS is the change in entropy.

We consider that the electrical cycle rejects its heat QR' to a water production cycle at the temperature T_2.

The work done in the water cycle would be:

$$W_W = (T_2 - T_0)\,\Delta S \qquad (2)$$

where: T_0 is the heat rejection temperature to the environment.

The combined electrical and water production cycle has a total work as:

$$
\begin{aligned}
W_{Total} &= W_E + W_W \\
&= (T_1 - T_2)\,\Delta S + (T_2 - T_0)\,\Delta S \\
&= (T_1 - T_0)\,\Delta S
\end{aligned}
\tag{3}
$$

We can write for the heat addition to the cycle:

$$Q_A = T_1\,\Delta S \tag{4}$$

The heat rejection from the combined cycle is:

$$Q_R = T_0\,\Delta S \tag{5}$$

The heat rejection from the electrical cycle to the water cycle can be expressed as:

$$Q_{R'} = T_2\,\Delta S \tag{6}$$

We can write expressions for the total cycle efficiency, electrical cycle efficiency and the water cycle efficiency. The total efficiency is

$$\eta_{Total} = \frac{W_{Total}}{Q_A} = \frac{(T_1 - T_0)\,\Delta S}{T_1\,\Delta S} = \frac{(T_1 - T_0)}{T_1} \tag{7}$$

The electrical cycle efficiency is:

$$\eta_E = \frac{W_E}{Q_A} = \frac{(T_1 - T_2)\,\Delta S}{T_1\,\Delta S} = \frac{(T_1 - T_2)}{T_1} \tag{8}$$

The water cycle efficiency is:

$$\eta_W = \frac{W_W}{Q_{R'}} = \frac{(T_2 - T_0)\,\Delta S}{T_2\,\Delta S} = \frac{(T_2 - T_0)}{T_2} \tag{9}$$

We wish to find the relationship between the three cycle efficiencies. Starting from Eqn. 7 and substituting from Eqn. 3 we get:

$$\eta_{Total} = \frac{W_{Total}}{Q_A} = \frac{(T_1 - T_2)\,\Delta S + (T_2 - T_0)\,\Delta S}{T_1\,\Delta S} = \frac{(T_1 - T_0)}{T_1}$$

This can be rewritten as:

$$\begin{aligned}\eta_{Total} &= \frac{(T_1 - T_2) + (T_2 - T_0)}{T_1} \\ &= \frac{(T_1 - T_2)}{T_1} + \frac{T_2}{T_1}\frac{(T_2 - T_0)}{T_2}, \forall T_2 \neq 0\end{aligned} \tag{10}$$

Substituting from Eqns. 8 and 9, we get:

$$\begin{aligned}\eta_{Total} &= \eta_E + \frac{T_2}{T_1}\eta_W \\ &= \eta_E + r\,\eta_W\end{aligned} \tag{11}$$

where: $r = \frac{T_2}{T_1}$.

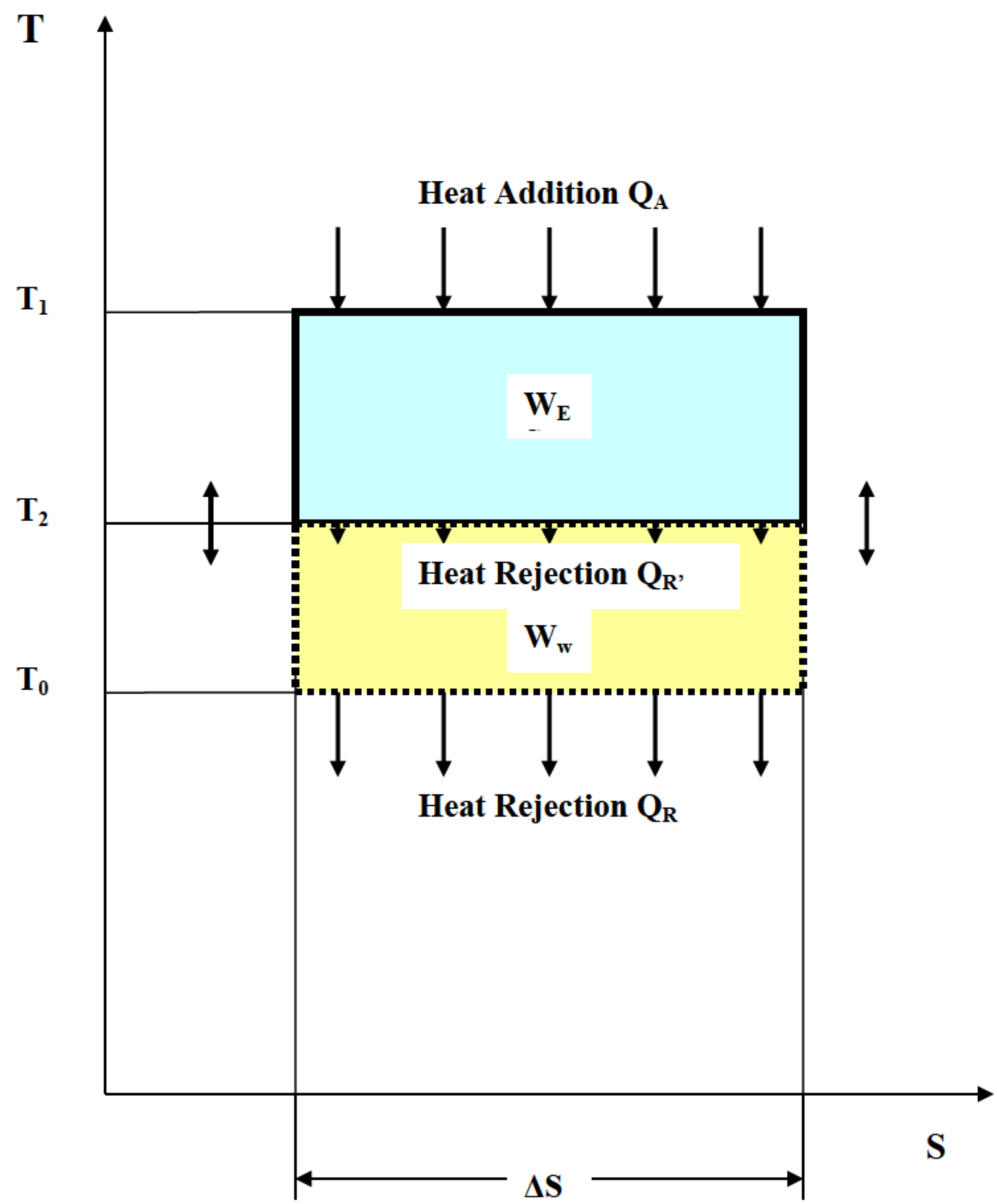

Figure 1. Single and dual purpose desalination plants Carnot Cycle efficiencies absolute temperature T versus entropy S diagram.

This suggests that the combined cycle efficiency is equal to the electrical cycle efficiency plus the water cycle efficiency weighed by the factor r which the ratio of the temperature at which the temperature at which heat is added to the water cycle T_2 to the temperature at which the heat is added to the electrical cycle T_1.

Table 1. Variation of the water, electricity and overall efficiencies for different transition temperatures, T_2. $T_0 = 273 + 20 = 293$ K, $T_1 = 273 + 320 = 593$ K.

Transition Temperature T_2 [K]	**Water Efficiency** $\eta_W = 1 - \frac{T_0}{T_2}$	**Electrical Efficiency** $\eta_E = 1 - \frac{T_2}{T_1}$	$r = \frac{T_2}{T_1}$	**Total Efficiency** $\eta_{Total} = 1 - \frac{T_0}{T_1}$
293	0.000	0.506	0.494	0.506
343	0.146	0.422	0.578	0.506
393	0.254	0.337	0.663	0.506
443	0.339	0.253	0.747	0.506
493	0.406	0.169	0.831	0.506
543	0.460	0.084	0.916	0.506
593	0.506	0.000	1.000	0.506

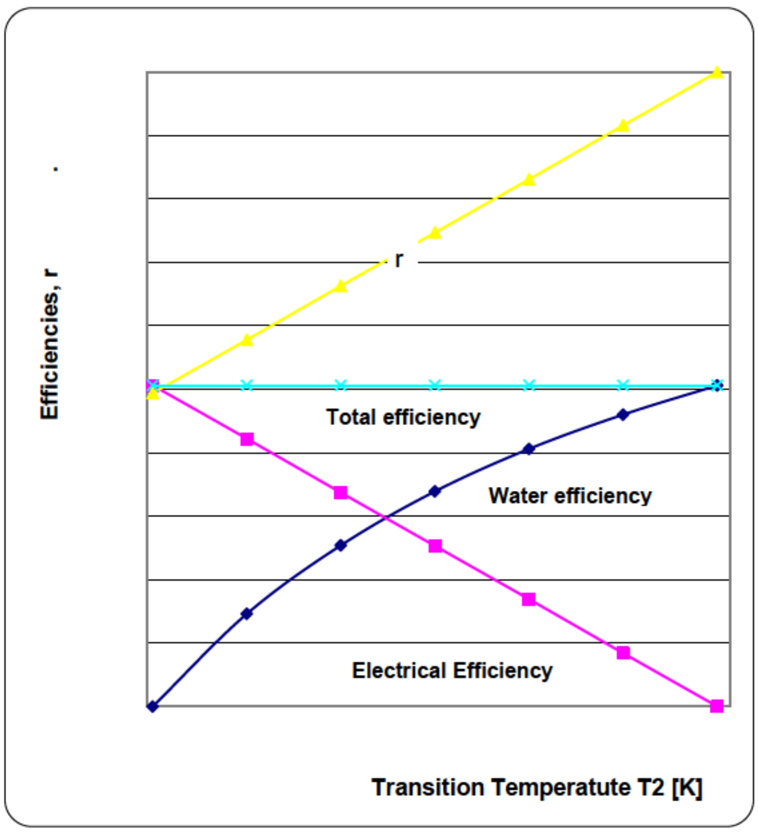

Figure 2. Water, electrical and total efficiencies and factor r as a function of the transition temperature T_2.

LIMITING CASES

The r factor can vary over the range:

$$\frac{T_0}{T_1} < r < 1 \qquad (11)$$

Since T_2 varies from an upper limit of T_1 to a lower limit of T_0, the upper limit of r is unity, and its lower limit is equal to the ratio of the temperature of heat rejection to the environment T_0 to the heat input to the cycle T_1.

This suggests a range of choices in terms of the relative magnitudes of the water production and electricity production processes. Their extreme cases lead to exclusive water production or exclusive electricity production processes.

In practice, operation will be at some intermediate value. However it can be noticed that the water production and electrical production processes are competitive rather than complementary. If one decides to produce a higher proportion of water, it is at the expense in terms of energy expenditure of the electrical process, and vice versa.

SINGLE PURPOSE WATER CYCLE

If we take the limit where r = 1 and consequently T_1=T_2 we get by substitution in Eqn. 10 and comparison with Eqn. 9:

$$\begin{aligned}\eta_{Total} &= \frac{(T_2 - T_2)}{T_2} + \frac{T_2}{T_2}\frac{(T_2 - T_0)}{T_2} \\ &= \frac{(T_2 - T_0)}{T_2}, \forall T_2 \neq 0 \qquad (12) \\ &= \eta_W\end{aligned}$$

This suggests a single purpose water production process.

SINGLE PURPOSE ELECTRICAL CYCLE

If we take the limit where $T_2 = T_0$ and consequently $r = T_0 / T_1$ we get by substitution in Eqn. 10 and comparison with Eqn. 8:

$$\begin{aligned}\eta_{Total} &= \frac{(T_1 - T_2)}{T_1} + \frac{T_2}{T_1}\frac{(T_2 - T_2)}{T_2} \\ &= \frac{(T_1 - T_2)}{T_1}, \forall T_2 \neq 0 \qquad (13) \\ &= \eta_E\end{aligned}$$

This suggests a single purpose electricity production process.

WATER AND ELECTRICITY MIX

We attempt a closer examination of the fresh water and electricity production mix under different situations.

Using Eqns. 1, 2 we can express the water to electricity work ratio as:

$$WE = \frac{W_w}{W_E} = \frac{(T_2 - T_0)\Delta S}{(T_1 - T_2)\Delta S} = \frac{(T_2 - T_0)}{(T_1 - T_2)}, \forall \Delta S \neq 0$$

Dividing into T1 and using the definition of r, we get:

$$WE = \frac{(\frac{T_2}{T_1} - \frac{T_0}{T_1})}{(1 - \frac{T_2}{T_1})} = \frac{r - \frac{T_0}{T_1}}{1 - r} \qquad (14)$$

where: $r = \frac{T_2}{T_1}$.

We can similarly define the electricity to water production ratio as:

$$EW = \frac{W_E}{W_W} = \frac{(T_1 - T_2)\Delta S}{(T_2 - T_0)\Delta S} = \frac{(T_1 - T_2)}{(T_2 - T_0)}, \forall \Delta S \neq 0$$

$$EW = \frac{(1 - \frac{T_2}{T_1})}{(\frac{T_2}{T_1} - \frac{T_0}{T_1})} = \frac{1 - r}{r - \frac{T_0}{T_1}} = \frac{1}{WE} \qquad (15)$$

Two limiting conditions can be noticed here.

If $T_2 = T_1$, r = 1, then EW = 0 for a dedicated water generation process.

On the other hand if $T_2 = T_0$, WE = 0 for a dedicated electrical production process.

Table 2. Water to electricity ratio WE as a function of $r = T_2/T_1$ for different values of T_0/T_1.

$r = \frac{T_2}{T_1}$	**Water to electricity ratio** $WE = \frac{r - \frac{T_0}{T_1}}{1 - r}$		
	$\frac{T_0}{T_1} = 0.25$	$\frac{T_0}{T_1} = 0.50$	$\frac{T_0}{T_1} = 0.75$
0.25	0.00		
0.30	0.07		

0.35	0.15		
0.40	0.25		
0.45	0.36		
0.50	0.50	0.00	
0.55	0.67	0.11	
0.60	0.88	0.25	
0.65	1.14	0.43	
0.70	1.50	0.67	
0.75	2.00	1.00	0.00
0.80	2.75	1.50	0.25
0.85	4.00	2.33	0.67
0.90	6.50	4.00	1.50
0.95	14.0	9.00	4.00
0.96	17.75	11.50	5.25
0.97	24.00	15.67	7.33
0.98	36.50	24.00	11.5
0.99	74.00	49.00	24.0

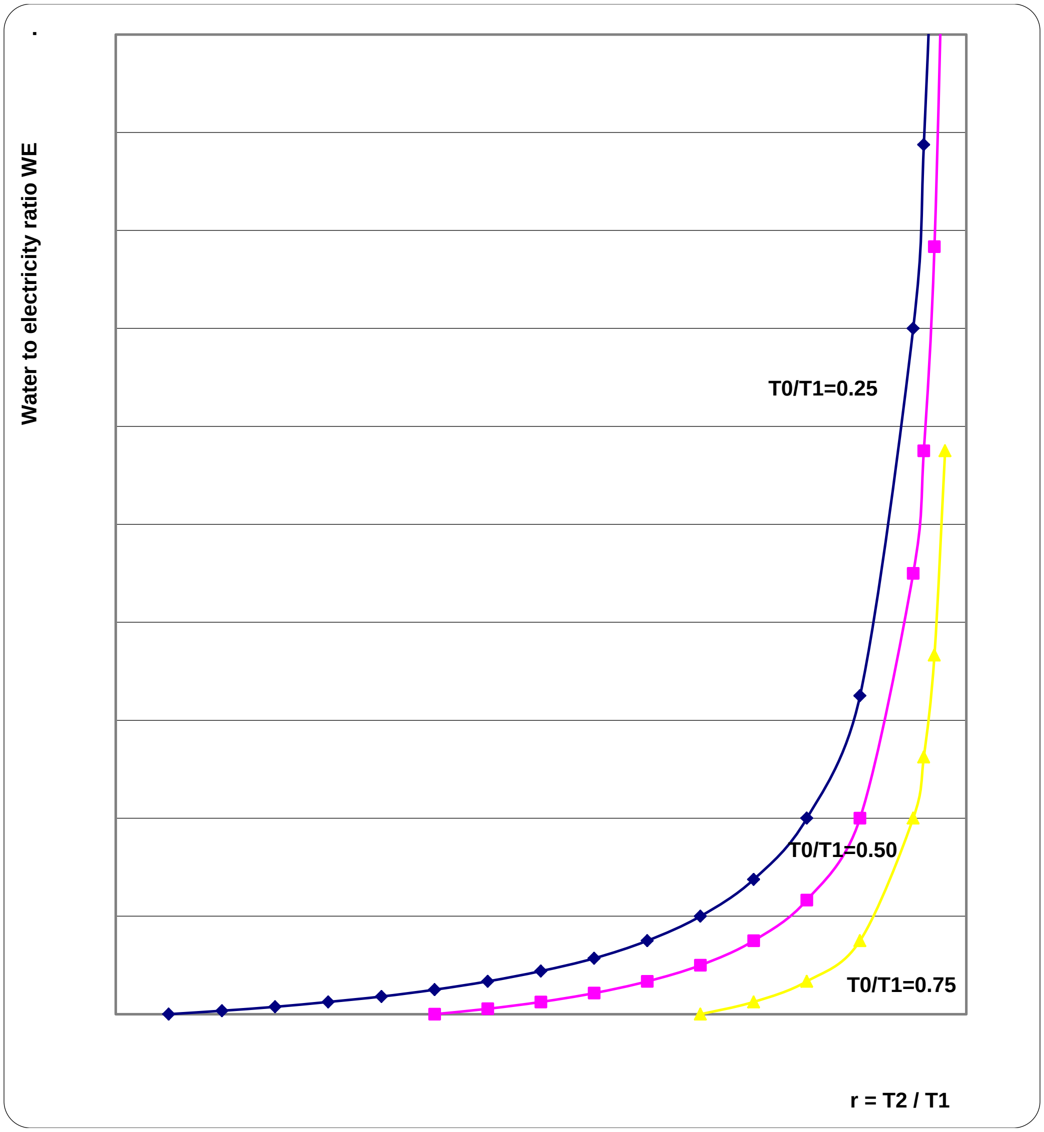

Figure 3. Water to electricity ratio WE as a function of r for different values of T_0 / T_1.

It can be observed that the water to electricity ratio WE increases abruptly as T_2 approaches T_1, or as r approaches unity, corresponding to a situation of a single purpose plant that primarily produces fresh water.

A low value of T_0/T_1 implies a plant operating at fairly low temperature, whereas a large value of T_0/T_1 corresponds to a plant operating at high temperature.

Since the rejection temperature T_0 is fixed by environmental considerations, we are limited to the freedom of increasing T_1. To increase the water to electricity ratio WE for a given heat addition temperature T_1, one must increase T_2, up to the point where $r = T_2 / T_1$ approaches unity. For instance, at a dedicated plant producing primarily water with $T_0 / T_1 = 0.25$ the water to electricity production ratio WE can reach a value of 74 when r = 0.99.

Table 3. Water to electricity ratio WE and electricity to water ratio as a function of r = T_2/T_1 for T_0 / T_1 = 0.25.

$r = \frac{T_2}{T_1}$	**Water to electricity ratio** $WE = \frac{r - \frac{T_0}{T_1}}{1 - r}$	**Electricity to water ratio** $EW = \frac{1 - r}{r - \frac{T_0}{T_1}}$
0.25	0.00	
0.30	0.07	14.29
0.35	0.15	6.67
0.40	0.25	4.00
0.45	0.36	2.78
0.50	0.50	2.00
0.55	0.67	1.49
0.60	0.88	1.14
0.65	1.14	0.88
0.70	1.50	0.67
0.75	2.00	0.50
0.80	2.75	0.36
0.85	4.00	0.25
0.90	6.50	0.15
0.95	14.0	0.07
0.96	17.75	0.06
0.97	24.00	0.04
0.98	36.50	0.03
0.99	74.00	0.01

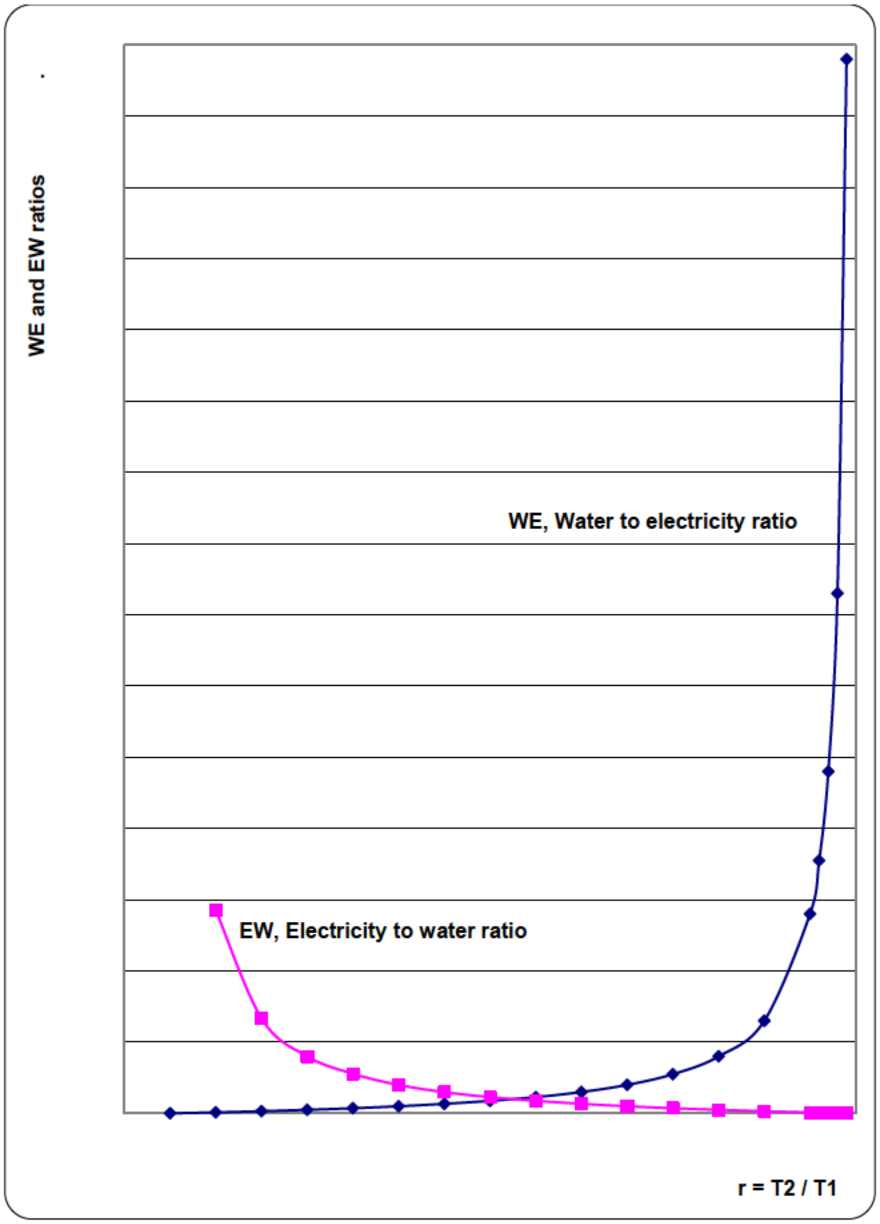

Figure 4. Water to electricity ratio WE and electricity to water ratio EW as a function of $r = T_2 / T_1$, for $T_0 / T_1 = 0.25$.

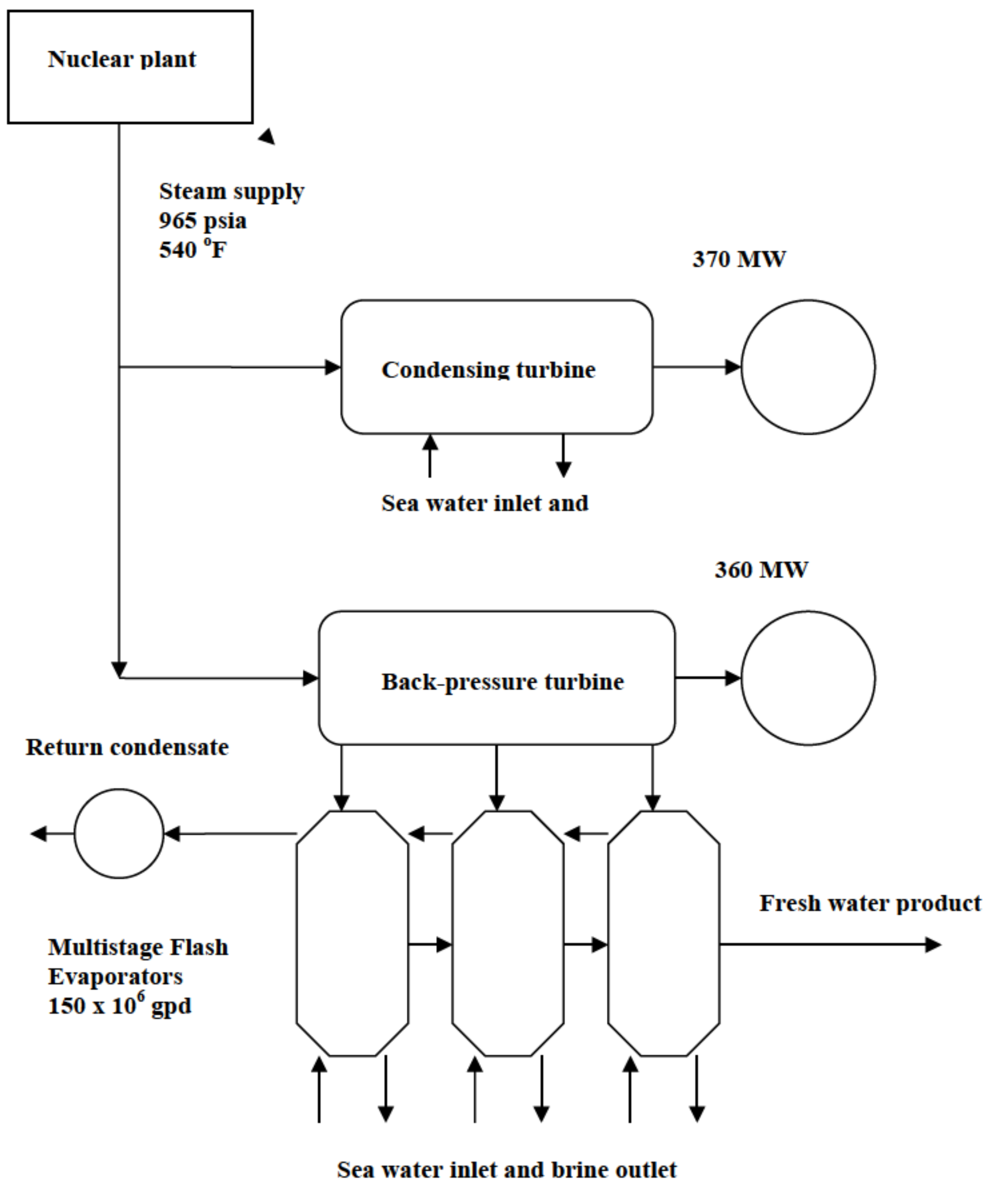

Figure 5. Configuration of dual purpose plant with an electrical power only section with a condensing turbine and a electrical and water section with a backpressure turbine.

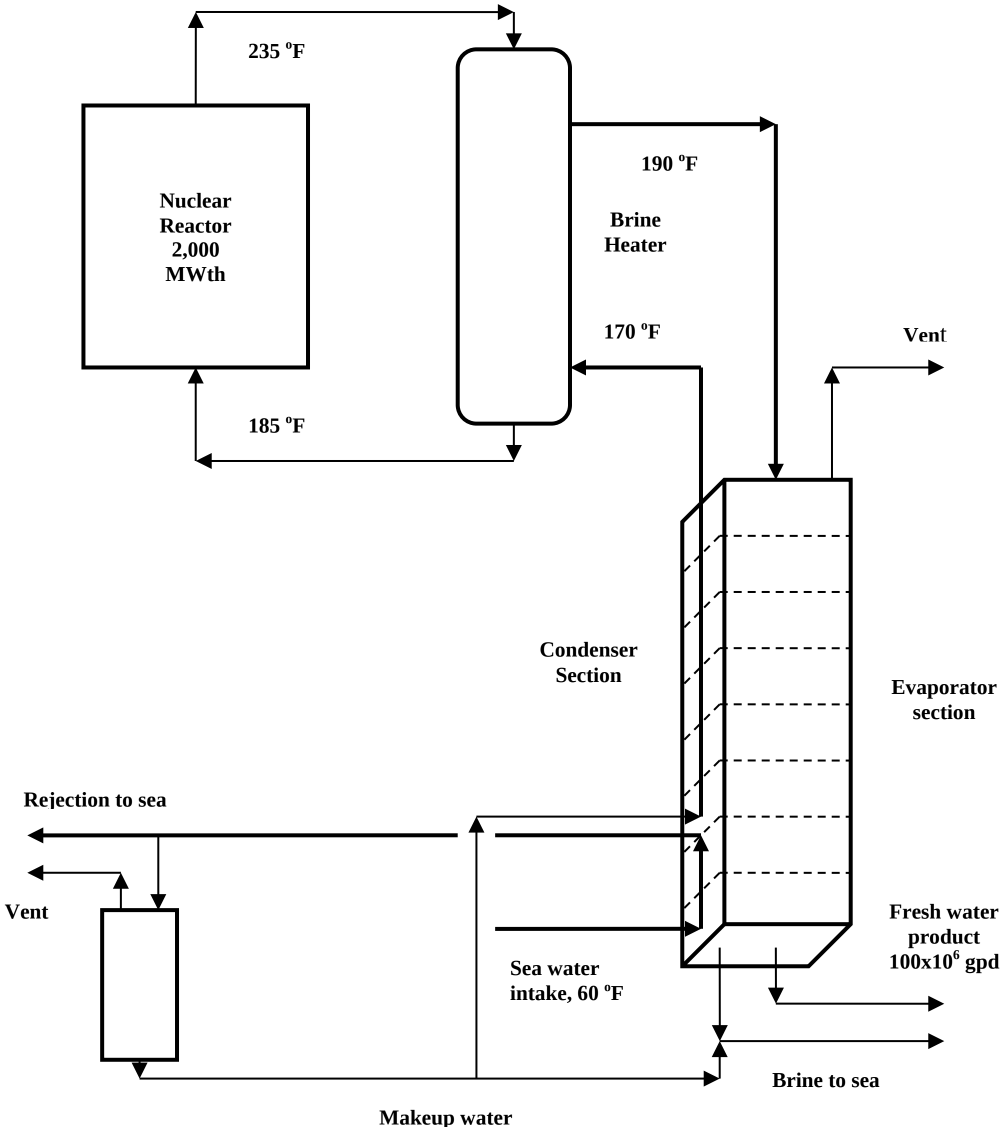

Figure 6. Low temperature single purpose producing 100 x 10^6 gpd of fresh water.

Table 4. Technical characteristics of a single purpose nuclear desalination plant [11]

Nuclear Island		**Desalinatiom Island**	
Power	2,130 MWth	Water production	100 x 10^6 gpd
Fuel	Natural U, UO_2	Evaporators	Controlled flash evaporation
Cladding	Al	Number of evaporators	28
Moderator/coolant	D_2O	Vertical stages per evaporator	10
Average fuel burnup	6.000 MWd/tonne U	Number of brine	14

		heaters	
Core fuel inventory	142 t UO_2	Heat transfer surface per brine heat exchanger	63,500 ft^2
Reactor vessel material	Al	Performance ratio	4.76 lbs water/1,000 BTU
Vessel height	37 ft	Evaporator height	40 ft
Vessel diameter	37 ft	Evaporator width	20 ft
Vessel thickness	2.5 in	Evaporator length	2.5 in
Core height	22 ft	Evaporator material	Copper-Nickel
Core diameter	22 ft		
Coolant flow	72.8 $x10^3$ gpm		
Primary coolant pumps	4	Sea water intake temperature	60 ^oF
Core inlet temperature	185 ^oF	Brine heater outlet temperature	190 ^oF
Core outlet temperature	235 ^oF	Brine heater inlet temperature	170 ^oF
Moderator inventory	$1.33x10^6$ lb		
Coolant loss	26,000 lb/yr		

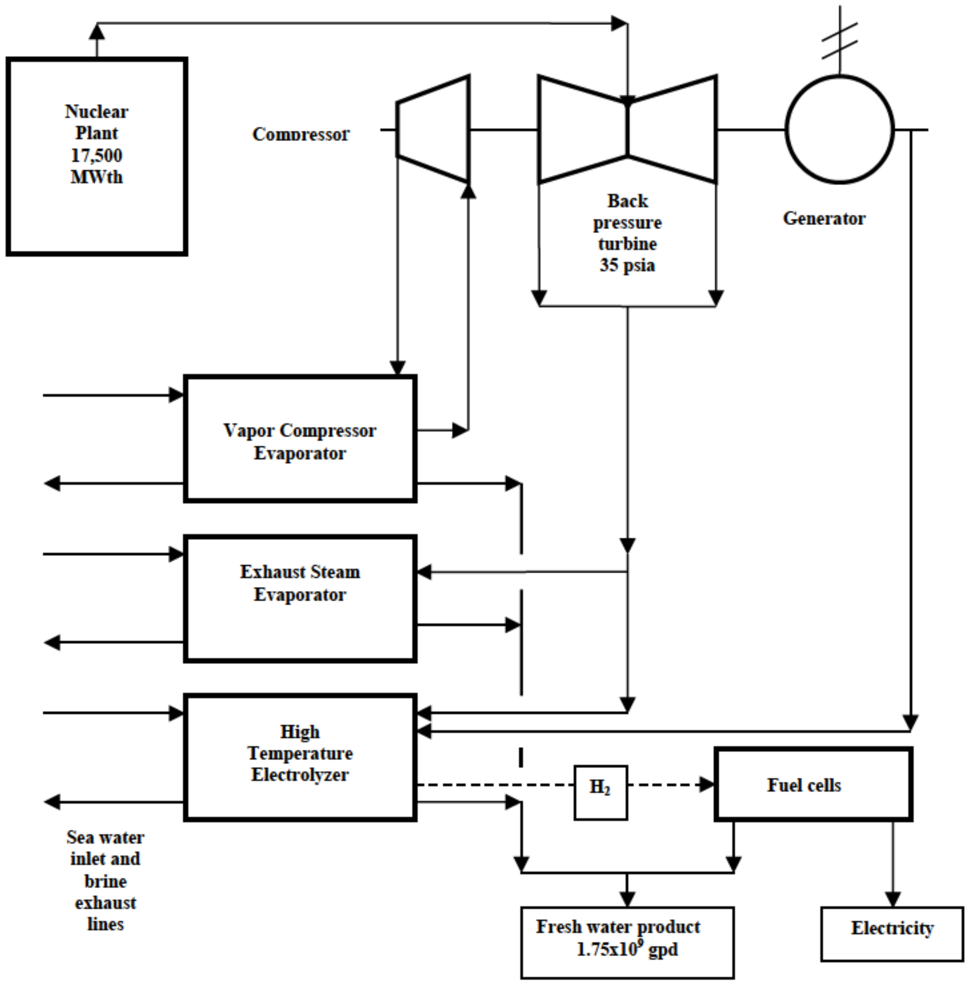

Figure 7. High temperature single purpose desalination plant configuration.

DISCUSSION

The thermodynamic analysis shows that it is not necessary to consider dual purpose desalination plants solely based on the intuitive belief that such an approach would be thermodynamically efficient through using the waste heat rejection from plants primarily designed to produce electricity and conveniently attaching to their back end water desalination plants. Instead, the plant must be designed according to the relative needs of water to electricity.

The water production process and the electricity production process are thermodynamically competitive rather than complementary from a Carnot cycle efficiency perspective. As the water cycle's efficiency increases, the electrical cycle's efficiency decreases; and vice versa.

Higher efficiencies of either process can be attained by rejecting the heat at the same ambient temperature T_0. This suggests the need for a close examination of the water and electricity production mix at the design stage of both the power source such as a nuclear reactor, and the chosen desalination plant. A desalination plant cannot just be fitted to the existing design of a power source.

Considering experience based upon operating nuclear power plants limits the transition temperature T_2 to 250 ^oF. For electricity production, the heat rejection temperature T_0 cannot approach greatly lower sink temperatures without an increase in cost associated with adding additional turbine stages. Similarly, increasing the water production efficiency by decreasing T_0 would require an increasing number of desalination stages.

In order to control scale formation in the distillation process the brine temperature will be based on the pressure under which the distillation process receives the process steam from the reactor. This pressure ranges from 0.37 MPa to 4.00 kPa.

Single purpose plants designed for specific applications operating at low temperatures and pressures and offering an even greater level of operational safety than high temperatures electrical production plants may be built with local simple technology and human resources. These would also provide ease of siting and construction using indigenous materials, while providing needed fresh water supplies and insuring the safety of the general population and environment.

REFERENCES

1. M. Ragheb, K. Toukan, and R. A. Al Weshah, "Desalination using Advanced design Nuclear Power Plants," Proceedings of the International Symposium on Water Resources in the Middle East: Policy and Institutional Aspects," Urbana, Illinois, pp. 173-180, 1993.
2. M. Ragheb and A. Siddique, "Single Purpose and Dual Purpose Nuclear Desalination Plants," Proceedings IXth World Water Congress Conference of the International Water Resources Association (IWRA), Montreal, Canada, September 1-6, 1997.
3. M. Ragheb and A. Siddique, "Thermal and Electrical Desalination using Fusion Cycles," 16th IEEE/NPPS Symposium on Fusion Engineering, Champaign, Illinois, Sept. 30-Oct. 5, 1995.
4. M. Ragheb and A. Siddique, "Thermodynamic Cycle efficiencies of Single Purpose and Dual Purpose Nuclear Desalination Plants," First TSS/ASTA International Conference on "Technology Parks and Transfer of Knowledge," Tunis, Tunisia, July 22-24, 1996.
5. R. W. Schleicher and C. J. Hamilton, "Exploiting the Nuclear Option for both Electricity and Water," American Power Conference 53rd Annual Meeting, Chicago, Illinois, April 29-May1st, 1991.
6. S. Postel, "Last Oasis: Facing Water Scracity," The Worldwatch Environmental Alert Series, W. W. Norton and Company, New York, London, 1992.
7. J. Kupitz, "Niuclear Energy for Seawater Desalination: Updating the Record," IAEA Bulletin, 2, pp. 21-24, 1995.
8. Grace M. Urrows, "Nuclear Energy for Desalting," USAEC, Division of Technical Information, 1967.
9. R. Philip Hammond, "Nuclear Desalting for Agricultural Water," Nucleonics, Vol. 23, No. 9, pp. 51-55, Sept. 1965.

10. Frederick E. Crever, “The Prospects for Dual-Purpose Plants,” Nucleonics, Vol. 23. No.9, pp.44-47, Sept. 1965.
11. S. Baron and M. Zizza, “Why Not Single-Purpose Reactors for Desalting?,” Nucleonics, Vol. 23. No.9, pp.48-50, Sept. 1965.
12. B. A. Gabaraev, Yu. N. Kuznetzov, A. A. Romenkov, Yu. A. Mishanina, “Nuclear Desalination Complex with VK-300 Boiling-Type Reactor Facility,” World Nuclear association, Annual Symposium, 2004.