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Desalination of Hyper-Concentrated Brines via Microwave Irradiation Mechanism: Case Studies. A Simultaneous Integration of Thermal Desalination, Steam Turbines, and Brine Mining into a Desalination Plant Design

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ABSTRACT

A new and novel approach to thermal desalination is being developed. This application involves microwave irradiation of custom-made reactors that can generate instantaneous temperatures of over 1000 °C and cause instant evaporation of seawater. The benefits are severalfold: in addition to purified water, suitable for human consumption, a large amount of energy can be generated via steam turbines that can be fitted into the desalination module. This approach also makes brine mining of rare metals possible, as large amounts of brine are generated and stored for further processing. The energy consumption is just a fraction of the conventional thermal desalination process. This approach can be transferred into portable desalination devices that can be easily deployed in emergency and distress situations.

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Introduction

Water scarcity today represents a global problem with no end in sight for at least a century, according to some estimations [1]. Global water demand, at an all-time high, is fueled by two main factors: 1) unprecedented population growth and 2) unprecedented economic growth. As such, it is exerting an extreme strain on the global capabilities of supplying fresh water to its citizens. Despite attempts by some countries over the last two decades or so to decouple the water demand from economic growth using smart water management systems and/or technology applications with minimal water demand, the current situation points to a tremendous water crisis that currently affects over 1.5 billion people with no direct access to potable water, and indirectly another 2 billion with a restricted access [1-5].

A sensible question posed by experts in this field is this: Are investments in expensive water-saving technologies justifiable? The logical answer is: No, as long as the water is cheaper than the technology in question. And the process that still enables the relatively low-cost drinking water is, of course, the process that separates dissolved solids from the freshwater, known as Desalination. This term refers to a number of approaches designed to produce potable water from either saline or other polluted water sources.

Desalination as a process of generating potable water has been in use since the beginning of the last century as an industrial process; however, it is clear today that despite new and novel desalination techniques used over the last decades, there is no end in sight for the water crisis. New desalination techniques, such as the one presented here, are needed to meet the water demand of the ever-growing global population.

Although this short article is not meant to be a general review of desalination techniques and methodology in general, the authors deem it necessary to present a brief overview of such techniques for comparison purposes.

Not considering its far more ancient origins, since the 1950s, desalination has become the most important industrial process of generating freshwater from seawater/ brackish water sources. Commercial desalination technologies can be generally divided into two categories: a) Thermal desalination technologies such as multi-stage flash distillation, multiple-effect evaporation, vapour-compression evaporation, cogeneration and solar desalination; b) Membrane technologies such as Reverse Osmosis (RO), Electrodialysis, Membrane distillation.

Thermal Distillation is probably the simplest (and oldest) method for producing drinking water from saline water sources, used by approximately 35% of desalination plants worldwide. The water steam is somehow captured and then condensed to generate 100% pure water. Conventional thermal distillation has been used for centuries; however, in recent decades its applications have dwindled due to copious amounts of heat needed for boiling water and producing steam. From an energy perspective it is estimated that up to 75% of operational expenses for a water distillation plant are related to energy costs [6-8]. For this reason, thermal desalination plants, are typically located in areas where the cost of fuel-generated heat is still among the cheapest on the planet, namely Middle East countries. A common energy usage unit in desalination planning, the Unit Production Cost for the thermal desalination plants is especially high, up to \$ 0.5 - 0.7 per gallon (\$ 0.125 - 0.175 per liter) of water produced in some cases, as compared to \$ 0.1 per gallon (\$ 0.025 per liter) or less, for the RO desalination technologies.

Almost every other country on Earth has adopted the Reverse Osmosis (RO) methodology in desalination, a technology that requires less energy, probably up to 45% of operating expenses but far more complex engineering infrastructure. The capital costs for RO plants can easily reach several hundred million dollars. The strong and weak points of both methodologies are widely known today and will not be discussed here; the focus of this article will be *a new thermal desalination technology, powered by microwave irradiation, which offers a different perspective both energetically and structurally. Whilst this approach respects the thermal desalination principles, the application is inherently different as the energy needed for the desalination process is generated remotely through microwaves*. This, on the other hand, brings a structural elegance and compactness not found in current conventional desalination applications. At this point, we take a brief moment to talk about microwave-assisted applications and especially focus on a very important question: Why have microwaves not been mentioned so far in desalination technology? The approach detailed in this article relies upon a new structural element, namely Microwave Sensitized Element (MSE), whose structure and function will be detailed in the following sections.

Introducing Microwave Sensitized Elements as the Basis for Our Non-Conventional Desalination Protocol

Since the beginning of this century, microwave-enabled technologies have been used at an ever-increasing pace in different areas of chemical, pharmaceutical and food industries. The advantages of a well-known approach today, Microwave-Assisted Organic Synthesis as an enabling technology, have led to its use in a wide variety of applications with close to 10,000 manuscripts published in this field [9,10]. Microwave-assisted protocols have been exploited successfully in drug discovery, total synthesis, biochemical processes, polymer synthesis, nanotechnology, and materials science [11-20]. A novel approach, that of Metals in Microwave was used successfully to reduce the flow process duration by 50-100 times via enhanced amplification of the heat delivered into the reaction medium through the use of extremely thin metal films designed to capture the microwave irradiation and generate heat (instead of irradiating directly the reaction mixture) [11]. This approach, credited with generating instantaneous temperatures that can reach values of over 1000 ºC on the process reactors, was a standalone example at the time of how expeditiously microwaves can generate heat in the presence of an extraordinary heating element such as a thin film [12,13].

The truth is that up to this moment, with the exception of a few laboratory-based experimental attempts mostly in academia to show the potential of microwaves in desalination, there are no known microwave-enabled desalination applications on an industrial scale. One of the main reasons is the fact that *microwaves by themselves cannot transfer sufficient energy to the water to successfully conduct thermal distillation in a timely manner.*

The appreciable heating of water by microwave irradiation, leading to the distillation process is severely hindered by two major factors: a - The minuscule microwave penetration depth of water (less than 2.0 cm at 25 ºC) that makes in-depth heating of large stagnant water volumes practically impossible, and b - The brief residence time for continuous water flowing through microwave chamber, often measured in seconds, makes the achievement of water temperatures of 100 ºC or more almost impossible for these large water volumes.

In order to ensure uniform heating of materials under microwave irradiation it is necessary to ***alter the thermodynamic properties of the system*** by introducing a carefully designed Microwave Sensitized Element (MSE), a structural element of the vessel/reactor that is directly under microwave irradiation [21,22].

Under microwave irradiation conditions, the MSE generates a significant amount of heat which is then transferred via a conductivity mechanism to fluids/materials present in the reactor. MSE is typically defined as an integrated module of composite materials with semi-conductive properties (including a metallic thin film that increases exponentially the rate of heat generation) that under microwave irradiation become fully conductive, unleashing profuse amounts of heat in the process.

The importance of MSE is significant: it removes the uncertainty associated with the generation of heat in microwave-irradiated materials either in flow format or stagnant situations. In order to generate a uniformly distributed heat throughout the microwavable zone, most materials should possess uniformly distributed microwave-active fluids such as water, capable of generating heat via a dielectric heating mechanism (dipolar rotation and ionic conduction); ensuring material uniformity however, is hard to achieve for a great range of processes that can be conducted under microwave irradiation.

The Function of MSE is Two-Fold

a) MSE enormously increases the heating efficiency of the system under microwave irradiation via fast generation of uniformly distributed heat within the body of the reactor. MSE alters the thermodynamic properties of the system by unleashing an abundant amount of latent energy stored in semi-conductive and conductive materials [6-10]. The heating efficiency of the system is thus increased hundredfold resulting in fast generation of uniformly distributed heat within the body of the reactor.
b) MSE ensures a reliable uniformity and quantification of the heat that is initially generated in the reactor and then transferred into the body of process materials. Not only is the heat generation profuse, but the reactor temperature can be readily measured by fiber optic and/or infrared sensor devices. This way, by simply increasing or decreasing microwave power, a reliable quantification of heat generated in the device is guaranteed.

The principle of this approach is dependent upon a carefully orchestrated balance between the composition and thickness of the MSE and the power of microwave irradiation. By fine-tuning this balance, the coupling of microwave irradiation to the MSE generates a profuse amount of heat via the resistive heating mechanism of microwave-induced currents in the body of the MSE. The heat thus generated is then transferred via a conduction mechanism from the reactor, into the body of process materials. The reactor can be perceived as having a cylindrical cavity for the flow through of fluids, however other shapes of the cavity are not excluded, for example, a rectangular or hexagonal shaped cavity.

In this regard, the uniformly distributed heat zone is typically represented by uniformly distributed temperatures, that can be conveniently assessed using sensitive Infra-Red temperature sensors or devices. This approach removes a big unknown from overall process equation: *The heat transferred into the body of process materials will no longer depend on the material composition, only the time these materials spend inside the microwave-irradiated reactor*. This way, a great range of materials with heterogeneous composition can achieve uniformly distributed heat under microwave conditions.

MSE elements are typically included in the structure of coil reactors situated inside microwave chambers, designed to reach and convey super-high temperatures over a brief interval under microwave irradiation conditions [21,22]. We refer to these reactors as MEFT (**M**icrowave **E**nabled **F**ast **T**ransfer) coil reactors (Figure 1).

Using this approach, ultra-high temperatures of over 1000° C can be achieved within seconds (Figure 2), while the microwave energy consumption is kept at only a fraction of the power (200 to 250 Watts) compared to the power normally needed by similar conventional devices, several KWatts.

In this regard, such technology can be among the greenest on the planet: microwave-powered devices can be supported comfortably by solar power modules or efficient fuel generators, a feature that renders these devices highly independent of the power grid.

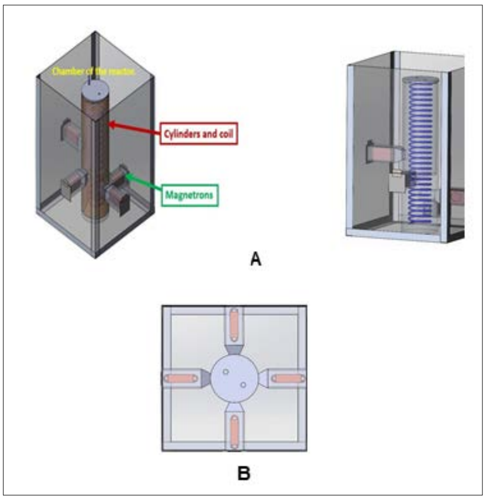

Figure 1: A) Side view of a single MEFT Coil Reactor inside the Microwave Chamber is shown at Different Angles. The Reactor is Surrounded by 4 Magnetrons Mounted on Chamber Walls; B) Top view of the Same MEFT Coil Reactor

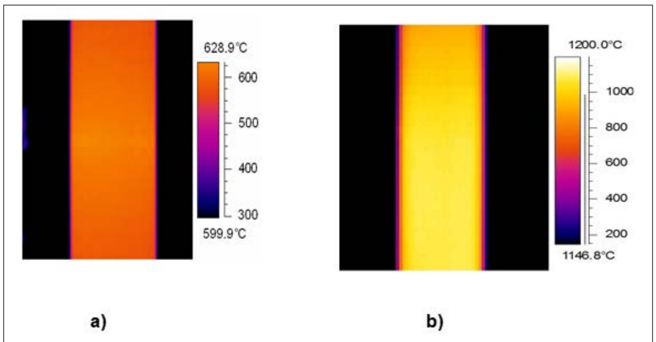

Figure 2: a) Infrared Image of a Partial MEFT Coil Reactor, obtained inside the Microwave Chamber using an Infra-Red Imaging Camera, Indicating the Uniform Temperature of over 600 °C throughout the Reactor Length; b) Similar MEFT Coil Reactor Reaching a Temperature of 1200 °C after Prolonged Time (Microwave Power used in both Cases is 250W)

The sphere of applications of this technology can be extended far beyond the typical range of in-flow chemical, pharmaceutical, and biotechnological processes, for which it was originally invented [12-20]. This technology can be used very successfully in food industry applications to conduct UHT (Ultra High Temperature) processing of liquid foods in flow format and very importantly swift pasteurization of milk, fruit juice, wine, beer, etc.

Among environmental applications, the thermal desalination of brackish/saline water and, certainly takes priority.

Other equally important industrial applications include instantaneous debacterification of industrial/urban liquid waste prior to discharge into the environment, brine mining for lithium, magnesium, and other rare elements via mining of hyper-concentrated brines from seawater, measured hydrogen generation through microwave-enabled treatment of hydrides, etc.

Desalinator in a Matchbox: A Portable MEFT Coil Thermal Desalination Device

A portable desalination prototype has been built using MEFT coil reactors as shown in Figure 3 (we call it Desalinator in a Matchbox). This unit, weighing approximately 15 kg, is typically designed to generate potable water from extremely polluted and/or hypersaline brines: it can generate up to 60 liters of drinking water per hour (approximately 1.0 Liter per minute); its energy requirements can be fully satisfied by solar modules; additionally, the lightweight portable fuel generators offer a much more compact and affordable alternative as an energy source.

Figure 3: Frontal View of the *Desalinator in a Matchbox* Prototype

The portable desalination unit prototype displayed in Figure 3 consists of 2 microwave chambers A hosting 4 separate MEFT copper coil reactors (2 per chamber) that are connected to a distribution manifold B that manages the brine flow rate inside the reactor. A 1.0 Kw magnetron is built inside each chamber approximately 20 cm from the outer ceramic casing of the MEFT reactors. The internal coil ID is 0.17 inch (4.32 mm) and the length is approximately 12 feet (3.65 m). The coils can be activated separately or at the same time, for maximum water throughput. The saline feed water is drawn into the unit via the rotary pump C using the feed hose D which can be extended several meters to reach the saline water source. The hose contains a stainless-steel wire mesh filter at the tip for the purpose of eliminating solid particles in the feed water that can negatively impact the process [23].

The desalination process is conducted inside MEFT coils under microwave irradiation conditions. The brackish/saline water reaches instant vaporization while passing through superheated coils and then the steam re-condenses in the condensation module E before being collected into the purified water tank. The entire process is conducted under a vacuum (generated by the vacuum pump F) and lasts only seconds. The desalination system throughput is typically proportional to the number of MEFT reactor units linked to the system and also coil dimensions. It can reach hundreds of gallons per hour because reactor dimensions can be varied within a wide range and more importantly the number of MEFT reactor units in the system can be increased severalfold with little regard for space because of their compact size. The operation of the device is shown in a real-time video presentation [23].

Although, the general design and modus operandi of the *Desalinator in a Matchbox* might appear similar to other thermal water purification devices, MEFT coils represent a breakthrough in thermal desalination technology. *MEFT Coil Reactors* provide a Clean Energy solution to desalination by bringing several advantages compared with conventional desalination protocols, as noted below:

1. Thermal desalination temperatures can be achieved almost instantaneously inside the desalination coils, which can be sustained with an extremely small energy requirement. This also ensures a uniform heat distribution along the entire reactor body will ensure that there are no “dead zones” inside the reactor. On this basis, the water flow rate inside the reactor can be greatly increased.
2. The remote energy distribution in microwave chambers results in a simplified technological application compared to conventional technology as gas burners and/ or electrical heat exchangers will be avoided; the overall system cost can be significantly reduced.
3. Microwave-assisted thermal desalination technology can generate drinking water from any polluted water sources, including concentrated brines or highly microbiological water. By comparison, the conventional RO technology is limited to desalination of saline waters of typically 35-40 Gr/L TDS content.
4. One very important added benefit is that this technology has the potential to greatly reduce brine as a desalination by-product (as explained in more detail in section 5). The dissolved solids are collected in a very, very concentrated, almost solidified paste-like material that can be used as a primary source for mining lithium, magnesium, and other rare metals. Most importantly, any potentially dangerous chemicals can be stored safely on the ground, avoiding seawater contamination. A great number of desalination plants worldwide, numbering over 16,000, generate approximately 150 million cubic meters of brine daily, which is discarded back into the sea.
5. Very importantly, the energy needed for desalination can be provided by solar power alone. Once the MEFT reactors reach the desired desalination temperature of 500 °C through continuous microwave irradiation at the maximum setting, the microwave power is reduced to a minimum setting that represents about 10% of the initial microwave power.

Results and Discussion

Once the *Desalinator in the Matchbo*x became fully operational after the *field test* (running it continuously for 120 minutes) we proceeded to test its suitability for generating purified water from brines with different TDS content. Initially, we focused on the optimization of the desalination protocol; for that reason, e series of run tests were devised during which the protocol parameters such as MEFT coil temperature and flow rate were varied.

Desalination Test Protocol

The protocol for testing the device was kept relatively simple. As a first step, both magnetrons inside the microwave chambers A were switched on simultaneously and run at full power for several minutes. The copper coil reactors inside the chambers would heat rapidly; the temperature was monitored via an IR sensor inside the chamber, reading the temperature on the ceramic outer casing of the reactor. Once the temperature approached the desired value, the magnetron power would be reduced progressively until reaching 1/10th of the initial power. The MEFT coil temperature, ranging from 100 °C to over 1000 °C, would be reached within 3-6 minutes. The device would run under these conditions for another 10 minutes to ensure that the temperature of copper coils inside the casing (containing a range of MSE elements in a certain order) would be at par with the temperature indicated by the infrared sensor. At this time, the feed hose D would be put inside a 20-liter brine tank, and both the vacuum pump F and the rotary pump C would be switched on. The brine would enter the bottom of each coil via the distribution manifold B, the water would evaporate at the point of contact with the heated copper coils, then the steam would exit the coils, passing on to the condenser where it would condense into hot water and be collected into 2-liter containers at the exit. The condenser temperature is kept the same as the room temperature due to a stream of circulating brine, also managed via manifold B. Every test was conducted in triplicate, and then the collected water samples (2.0 liters each) would be mixed in a larger vessel from which a 10 mL aliquot would be collected and refrigerated before being sent for analysis. After each run, the MEFT coil reactor would be cleaned by running distilled water through at 300 °C to dissolve any salt buildup on the coil surface. The salt buildup is inevitable once the water evaporates inside the coil, especially for concentrated brine solutions.

Temperature Studies

Using the test protocol as described in Section 4.1 a series of tests were conducted to establish the optimal desalination temperature. This data is necessary to ensure a smooth device operation. The MEFT coil reactors can reach an exceptionally wide range of temperatures (from 100 °C to 1200 °C as described in Section 2, Figure 2). However, running the desalination device at insufficient desalination temperatures would affect the efficiency of the desalination process, whereas keeping the MEFT reactors at unnecessary high temperatures would damage the reactor coils.

The temperature studies were conducted using a 50 Gr/L TDS brine solution, which has only a slightly higher level of Total Dissolved Solids (TDS) than the typical seawater. The brine solution was prepared by dissolving 500 grams of table salt (NaCl) in 10 liters of distilled water.

The test runs were conducted at six distinct temperatures, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C. Higher temperatures were deemed unnecessarily high for the purpose of the desalination process. The device was kept running until a 2.0-liter sample of desalinated water was collected. After the test, a 10.0 mL aliquot was collected from all the condensed, desalinated water samples and analyzed for TDS content.

The results are shown in Table 1 below.

Table 1: TDS Levels of Condensed Water Samples in the Temperature Study Trials

MEFT Reactor Temperature (°C)	100	200	300	400	500	600
Condensed Water TDS (Gr/L)	50	28	5	< 1.0	< 1.0	< 1.0

It can be seen clearly from the results that MEFT coil temperatures of 100 °C and 200 °C are insufficient for the desalination process. The brine solution cannot fully evaporate, and therefore part of the brine is discharged as liquid into the collection vessel. At 300 °C, the situation begins to change, and 400 °C proves sufficient for the full evaporation of the brine solution. Temperatures equal to or above 600 °C are unnecessary, as the desalination can proceed successfully at lower values. The TDS level of the condensed water is approximately 1.0 Gr/L. The device removes approximately 98% of the initial TDS content; however, the efficiency does not improve with temperatures over 400 °C.

On this basis, a middle-range temperature such as 500 °C was chosen as the optimal temperature for the main desalination studies shown below.

Desalination of Brine Solutions

After the temperature studies were completed and a suitable temperature for the brine desalination process was established at 500 °C, a series of brine solutions with different levels of TDS content were prepared. In a typical fashion, a 10-liter brine solution was prepared for each TDS level by dissolving a certain amount of table salt (NaCl) into a container of distilled water and bringing the volume to the 10-liter mark by adding additional water. Using this simple protocol, several brine solutions were prepared over the course of several days, containing specifically 10 Gr/L, 25 Gr/L, 75 Gr/L, 50 Gr/L, 100 Gr/L, 125 Gr/L, 150 Gr/L, and 200 Gr/L dissolved salt (TDS levels). All these solutions, and also a tap water sample and a water sample collected from Lake Ontario, were tested on the Desalinator in the Matchbox using the optimized test protocol as described in Sections 4.1 and 4.2. The tests were run in triplicate, keeping the MEFT reactor temperature at 500 °C for the duration until a 2-litre sample was collected for each run; all three samples were mixed at the end of the runs, and a 10 mL aliquot was extracted from the mixture and refrigerated. Eventually, all the samples were tested for TDS and bacterial content.

The results are shown in Table 2 below.

Table 2: TDS and Bacterial Levels of Desalinated 2.0-Liter Water Samples from Brine Solutions Evaporated in MEFT Reactor Coils at 500 °C

Brine solution TDS (Gr/L)	**Tap water**	**Lake Ontario**	**10 Gr/L**	**25 Gr/L**	**50 Gr/L**	**75 Gr/L**	**100 Gr/L**	**125 Gr/L**	**150 Gr/L**	**200 Gr/L**
Condensed water TDS (Gr/L)	<0.001	<0.001	<0.01	<0.01	0.98	5.0	21.8	22.8	24.4	25.8
Total Bacterial Count	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected

The device is certainly suitable for the desalination of brackish water originating from lake or river sources. In such cases, the TDS content of such water sources (less than 1.0 Gr/L in most cases) will not affect the MEFT coil performance even in long runs. In order to confirm these results, the desalination protocol for the first 6 solutions in Table 2 was extended to obtain a 20-liter sample (instead of a 2.0-liter sample). A single test was conducted with the MEFT reactor running at 500 °C for approximately 20-25 minutes until a 20-litre sample was collected; then a 10 mL aliquot was obtained and tested for TDS and bacterial content. The results are displayed in Table 3.

Table 3: TDS and Bacterial Levels Of 20.0-Liter Desalinated Water Samples from Brine Solutions Evaporated in MEFT Reactor Coils at 500 °C

Brine solution TDS (Gr/L)	**Tap water**	**Lake Ontario**	**10 Gr/L**	**25 Gr/L**	**50 Gr/L**	**75 Gr/L**
Condensed water TDS (Gr/L)	<0.001	<0.001	<0.1	2.2	3.9	9.5
Total Bacterial Count	None Detected	None Detected	None Detected	None Detected	None Detected	None Detected

The device's performance has remained constant in one respect: it has completely eradicated any bacterial cultures contained in the brackish water samples; those samples were left for at least a week in open air to ensure the development of any biological cultures (no data was collected however as to the Total Bacterial Count of the brine solutions before the desalination).

This is probably to be expected, considering the 500 °C temperature at which the MEFT reactor coils in direct contact with water were kept during the desalination protocol. The instant vaporization of water in contact with the hot inner surface of the coils destroys instantly any biological cultures contained in brackish water.

When it comes to the desalination of supersaturated brines, the results are somewhat mixed. The data in Tables 1 and 2 indicate that the device is certainly suitable for the desalination of brackish water from a freshwater source such as Lake Ontario. The TDS content of lake waters is much less than 1.0 Gr/L, and the inner coil surface of approximately 1980 cm2 for the four MEFT reactors is certainly capable of retaining the small amount of dissolved solids once the water evaporates, even for relatively long times of operation. The device is also capable of handling light brines with TDS levels of 10-25 Gr/L; however, the brines with higher TDS levels, including the seawater, can only be desalinated for very short amounts of time. Once the water vaporizes in the MEFT coils, a substantial amount of solids is left behind, clinging to the coil surface. The superheated steam in later stages can then carry forward some of the smallest salt particles through to the condensation module and further on to the collection container of the desalinated water.

It is probably worth mentioning that this limitation of the *Desalinator in the Matchbox* device has been corrected in the large-scale desalination plant detailed in Section 5. The design of such a plant has been suitably altered to allow for the successful processing of supersaturated brines.

Large-Scale Desalination Plant Design using MEFT Coil Reactors

Using the technological principle of the portable *Desalinator in the Matchbox* as described in Section 3, a large-scale thermal desalination plant will be built, using a series of MEFT coils in the desalination module. The plant will be suitable for desalinating both lake/river and seawater sources; it will be capable of handling any range of TDS levels and will also be able to operate separately from the electricity grid (for this purpose, a solar module will have to be built, together with an energy storage bank).

A flow diagram of the thermal desalination process is shown in Figure 4.

The main component of the plant is the Microwave Enabled Distillation module, which derives saline water from the Saline Water Intake module located close to sea water line. After the desalination process the distilled water undergoes re-mineralization to establish the necessary amount of minerals before distribution to the consumer. The Power Plant provides power only in the initial start-up phase as the rest of the energy will be provided by the steam turbine generator (Figure 5).

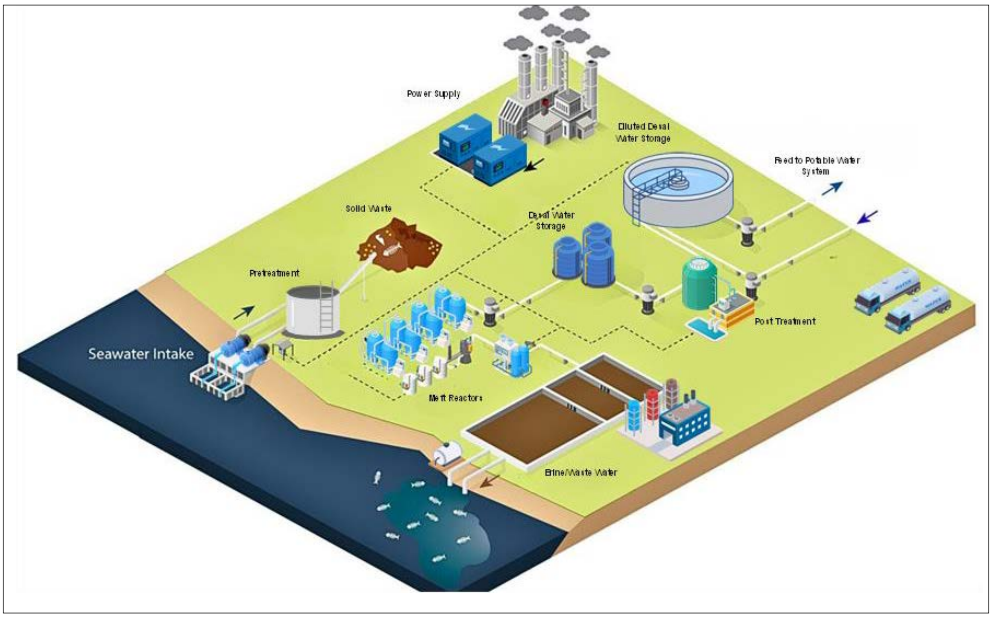

Figure 4: Flow Diagram of the Proposed Desalination Plant

1. **Seawater Intake:** Seawater is drawn from the Sea via four caged intake pipes located on the seabed, about 300 meters offshore and 25 meters below the sea surface. The flow rate of seawater entering the intake tunnel is quite slow, less than 1.0 m/s, and substantially less than seawater currents in the area. This will allow the local marine life to swim out of the tunnel and not get drawn into the Plant.
2. **Screening and Pre-Treatment Filtration:** Drum screens are used to remove any large materials that may enter the Plant through the intake tunnel. Typically, this is man-made rubbish and pieces of shells or plant matter from the ocean. We fill one small residential sized rubbish bin each month, on average. The Plant's pre- treatment filter system removes any solid material, such as algae and small dirt particles, from the seawater. The aim is to get the seawater as clean as possible prior to the thermal distillation process.
3. **Microwave Enabled Thermal Distillation:** The microwave-enabled distillation plant incorporates several modules of MEFT reactors. Each module is capable of desalinating between 1500 to 2000 gallons (6000 to 8000 liters) of freshwater/hour. The optimal operating conditions are defined according to situations; the equipment is tested over the long term to optimize the process.
4. **Post Treatment:** The fresh water produced by the microwave enabled thermal distillation process requires minerals to be added before preservation in line with Canadian Drinking Water Guidelines. Water quality tests are carried out before the fresh water is sent to the Drinking Water Storage Tank, which can hold 40 million liters or the equivalent of 16 Olympic-size pools.
5. **Water Supply:** Two large pumps will transfer the water from the Drinking Water Storage Tank into a 3-kilometer pipeline that passes under the Bay and connects to the Water supply network. The water is then distributed to the consumer through the supply network for consumption.

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Microwave-Enabled Desalination Plants: Drinking Water Production, Energy Generation, and Brine Mining

The main advantage of this plant (Figure 5) will be its uncharacteristically low energy consumption and the wide range of untreated water sources that can include any seawater/brine source, industrially and bacteriologically polluted waters. The use of microwave-enabled MEFT reactors means that this plant will experience none of the technical or cost-related issues associated with RO membrane technology (fabrication complexity, fouling, etc.).

The necessary energy for heating the desalination module comprised can also be provided by solar power modules that can be either set up as a land platform with all necessary components or a floating sea platform. The latter can be especially convenient with regard to cost and maintenance if the desalination plant is situated near the coastline.

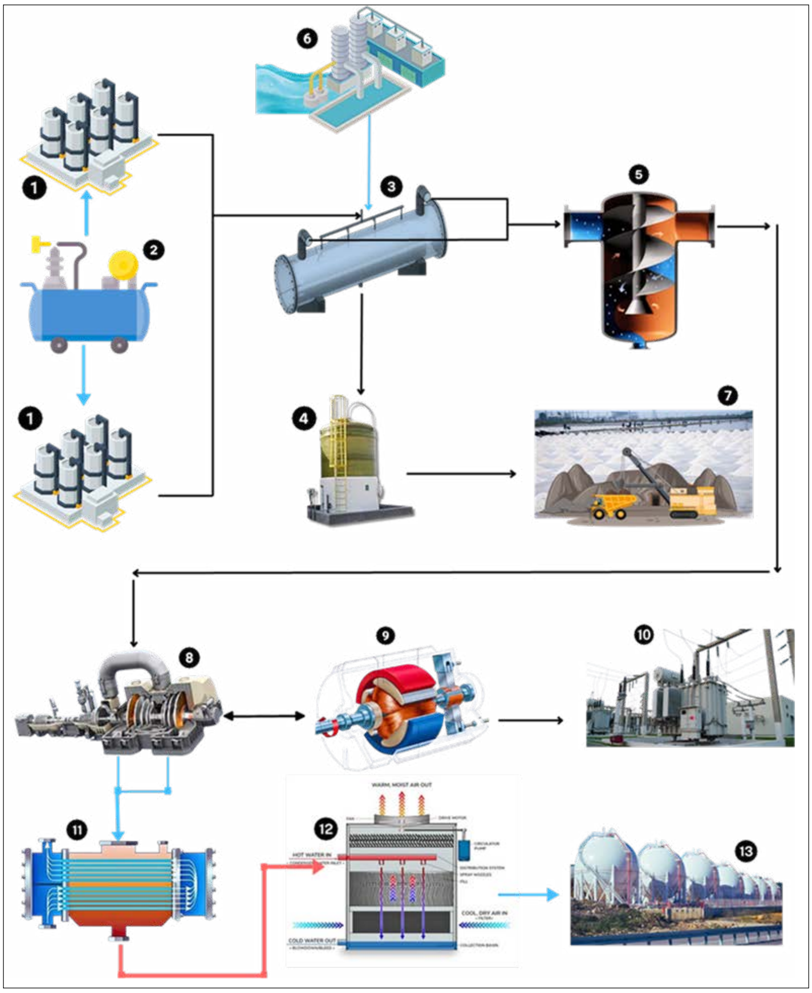

Figure 5: Detailed Thermal Desalination Plant Schematic that Incorporates MEFT Coil Reactor Technology

1. Microwave Module Accommodating 6 MEFT Reactors; 2. Air Compression Unit; 3. Initial Stage Evaporator; 4. Brine Water Treatment Module; 5. Cyclone Heat Exchanger; 6. Sea Water Intake with Screening and Filtration; 7. Brine Mining Operation; 8. Steam Turbine; 9. Generator; 10. Transformer Station; 11. Steam Condenser Module; 12. Cooling Tower; 13. Re-Mineralization Module and Potable Water Tank

Six cylindric reactors stand at the center of the rectangular microwave chamber **1**. The reactors consist of two coaxial cylinders with different inner diameters (ID). The outer cylinder, in direct contact with microwave irradiation, is typically made up of a temperature-resistant ceramic. The inner cylinder is stainless steel or other heat-resistant material. The stainless-steel coil sits in the middle of the cylinder. The Microwave-Sensitized Elements (MSE) are located in the space between the two coaxial cylinders and also between the inner cylinder and the coil in a prearranged fashion, so the maximum heat is generated within the MEFT reactor in the shortest possible time. The coil temperature is typically maintained at approximately 600 °C, however, far higher temperatures can be achieved. The MEFT reactor coils vary in ID from 1.25 – 2.5 cm and 6-8 m in length for a 2.0 m reactor height.

There are four 0.5 KW Magnetrons (microwave generators) located in their waveguides (small tunnel-like chambers that guide the microwaves into the chamber where the reactor is located). The magnetrons are placed in all four chamber sides at different heights to ensure a uniform distribution of microwave irradiation within the chamber. The magnetrons are designed to deliver full power for 4-5 minutes until the desired temperature of 580-600 °C is reached, then the microwave power drops to a fraction of the initial magnetron

power. The temperature inside microwave chamber 1 is strictly maintained below 50 °C through a cold air recirculation system not shown here.
Once the desired reactor temperature has been reached the microwave power drops to a small fraction of magnetron power as MEFT reactors are capable of retaining the temperature with a minimum microwave power. The temperature inside the microwave chamber is maintained below 50 °C through a cold air recirculation system (not depicted here).

The air compression unit **2** delivers pressurized air from the bottom of the reactors in microwave chamber 1; once the air reaches the reactor temperature, it exits from the top under high pressure to reach the initial stage evaporator **3,** where it is delivered inside the cold-water mass, coming from the seawater intake station **6** via the "shower head" distributor. The "wet" steam that is instantly generated inside the evaporator containing salty water is then directed to the cyclone heat exchanger **5** where it is mixed with a fresh stream of hot air causing instant drying. The over-pressurized steam then enters the steam turbine **8** with a 50 KW capacity that is connected to generator **9**. The generated electricity is rerouted to the end consumer via transformer station **10**. Once the steam leaves the turbine, its temperature drops significantly. It then enters the condenser unit **11** (and then cooling tower **12**). The condensed water is then directed into the re-mineralization unit **13** where the necessary minerals are restored in order to generate potable water that is stored in potable water tanks before the final delivery to the customers. The excess brine is transported to brine module **4** in order to be converted into dry salt, rich in heavy metals, and then shipped to brine mining plant **7**.

This Technology Boasts a Range of Substantial Benefits

1. **Clean Water Production:** The minimal plant design will have 5-20 integrated MEDU units. (Figure 5 depicts a single MEDU unit having 2 chambers by 6 MEFT reactors each). Every unit will be able to generate a minimum of 100 m3 of potable water per day which means that the entire plant will be able to generate at least 500 - 2000 m3 daily.
2. **Electricity Production via Steam Turbines:** The 50 KWH steam turbines for each unit will be able to produce approximately over 1000 KW of electricity in 24 hours (including a generous 4-hour downtime allowance for daily maintenance).
3. **Brine Accumulation for the Brine Mining Industry:** The process of seawater desalination will be able to accumulate over 100 tons of salt daily, rich in heavy metals.

The Future of Microwave-Assisted Desalination: Applying Artificial Intelligence (AI) in Conjunction with Microwave-Assisted Technology to Reduce Water Toxicity for Sharp Technological Applications

The microwave-enabled thermal desalination protocol generates extremely clean water for drinking purposes that is over 99.9% pure. However, this purity is still not suitable for technological and medical applications that need a TDS content of less than 0.001%. Water purity of this scale is only achieved through the combination of desalination with ion exchange purification protocols.

Another problem that was not fully addressed in this study is the optimization of the protocol for reducing polyfluoroalkyl substance (PFAS) toxicity and bacterial content. Whereas bacterial content can be kept in check through temperature optimization, as we have shown in this study, we believe that the PFAS toxicity can be reduced through the application of AI programs within this technology [24].

Incorporating AI with the right data sets at the right time is key to benefiting from Machine Learning and Deep Learning for toxicity prediction. Implementing different algorithms focused on predicting toxicity is applied to various water resources management methods to improve monitoring, prediction, and sustainable use of water resources. The work is designed to predict toxic liabilities in a general manner as the first phase.

The Structure for this Approach will be as Follows

1. Defining toxic endpoints
2. Determining the data set
3. Combining algorithms for Machine Learning constructions (regression and classification)
4. Interpreting the results based on different data sets.

One of the algorithms to be used is the **eToxPred** algorithm, as the Machine Learning models are trained and cross-validated with several data sets.

A detailed account of this elegant application will be given in the next article of this series [24].

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