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REVIEW PAPER

ATMOSPHERIC WATER VAPOUR PROCESSOR DESIGNS FOR POTABLE WATER PRODUCTION: A REVIEW

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Abstract—Atmospheric water vapour processing (AWVP) technology is reviewed. These processors are machines which extract water molecules from the atmosphere, ultimately causing a phase change from vapour to liquid. Three classes of machines have been proposed. The machines either cool a surface below the dewpoint of the ambient air, concentrate water vapour through use of solid or liquid desiccants, or induce and control convection in a tower structure. Patented devices vary in scale and potable water output from small units suitable for one person's daily needs to structures as large as multi-story office buildings capable of supplying drinking water to an urban neighbourhood.

Energy and mass cascades (flowcharts) are presented for the three types of water vapour processors. The flowcharts assist in classifying designs and discussing their strengths and limitations. Practicality and appropriateness of the various designs for contributing to water supplies are considered along with water cost estimates. Prototypes that have been tested successfully are highlighted.

Absolute humidity (meteorological normals) ranges from 4.0 g of water vapour per cubic metre of surface air in the atmosphere (Las Vegas, Nevada, USA) to 21.2 g m^{-3} (Djibouti, Republic of Djibouti). Antofagasta, Chile has a normal absolute humidity of 10.9 g m^{-3}. A 40% efficient machine in the vicinity of Antofagasta requires an airflow of 10 $m^3 s^{-1}$ to produce 3767 l of water per day. At a consumption of 50 l per person per day, 75 people could have basic water requirements for drinking, sanitation, bathing, and cooking met by a decentralized and simplified water supply infrastructure with attendant economic and societal benefits. © 2000 Elsevier Science Ltd. All rights reserved

Key words—water vapour, potable water, precipitation enhancement, water resources, desalination, review

INTRODUCTION

Innovations in water supply technologies are sought. "Basic concepts and philosophies of water development are undergoing fundamental changes" and "Major new projects are going to compete with new opportunities for innovative smaller scale, locally managed technical, institutional, and economic solutions to water quality and quantity problems" (Gleick, 1998, p. 32).

Innovative thinking applied to access "the last oasis", referring to vast amounts of water lost daily through inefficiency, mismanagement, and waste (Postel, 1992), has a tremendous payoff on the demand-side. Even so, the supply-side needs improvement.

Atmospheric water vapour processing (AWVP), is a relatively unknown option for smaller scale, locally managed water supplies. The water resources community needs to have an understanding of AWVP and be involved in its development.

Innovative sources of potable water are in use and were reviewed by the United Nations (1985). Desalination and cloud seeding are well-known innovations with high monetary and environmental expenses. Open-cycle Ocean Thermal Energy Conversion (OTEC) is another method of fresh water supply. Rain water harvesting (Gould, 1995) is a useful simple technology. Fog water harvesting (Cereceda *et al.*, 1992) uses modern materials in long lasting, simple devices that can be maintained with minimum outside expertise. AWVP has appeared sporadically in the literature (Gerard and Worzel, 1967, 1972; Hellström, 1969; Landsberg, 1972; Starr *et al.*, 1972, 1974; Rajvanshi, 1981; Seymour and Bothman, 1984; Elmer and Hyde, 1986; Khalil, 1993; Wahlgren, 1993; Nilsson *et al.*, 1994; Beysens, 1995; Nikolayev et al., 1996; Beysens *et al.*, 1998).

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ATMOSPHERIC WATER VAPOUR PROCESSING

Three types of devices, which handle water vapour differently have been developed (Fig. 1). Each cubic metre of air throughout Earth's 100–600 m thick atmospheric boundary layer contains 4–25 g water vapour, potentially allowing water supplies almost anywhere people inhabit. Landsberg (1972) charted the average amount of atmospheric water vapour resource available at Earth's surface in January and July. Regions at latitudes north or south of 30° subject to more than occasional frost (Lowry, 1972, Fig. 3.11), or at frost-prone altitudes would not be ideal locations, but populations in these areas usually have adequate water supplies. Other conventional and innovative water sources have physical and economic limitations of site and distribution which are well-known in regions of water scarcity. These regions are often situated in densely populated, developing countries in arid, frost free zones and include parts of the Caribbean and much of: Central America, South America, Africa, the Middle East, and Southern Asia. The desperate need to provide even minimum requirements to 1300 million people lacking potable water (1990 estimate; Gleick, 1998, p. 40), with affordable capital and operating costs, is the driving force for developing AWVP.

AWVP is a young technology with the potential of being made appropriate, community-managed and community-maintained in the context of developing countries. AWVP installations could be competitive with desalination plants of similar water output but have the advantage of being simpler and less expensive to operate and maintain. Water production depends on installation size but would range from several litres to millions of litres daily. AWVP is suitable for providing drinking water to individuals and neighbourhoods of hundreds or thousands of people. Taking advantage of minimal location constraints for AWVP, need for expensive water distribution infrastructure can be reduced or avoided.

The large energy requirement for changing water

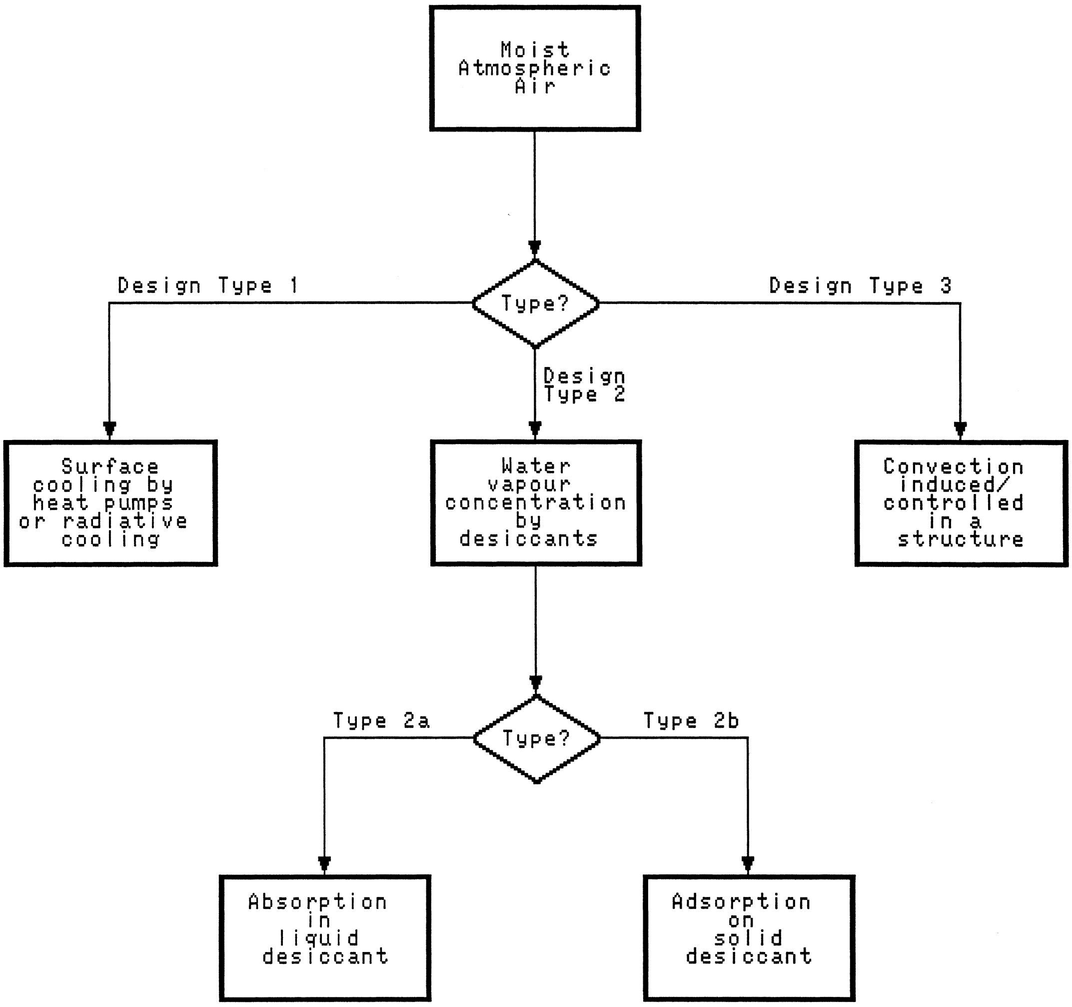

Fig. 1. Atmospheric water vapour processor design types overview.

Table 1. Energy requirements of desalination compared to AWVP for producing 1 m^3 of fresh water

Item	Energy (kWh/ m^3)	Annual energy use analogy (after Strauss, 1995, p. 145)
Desalination: Theoretical minimum energy needed to remove salt from seawater (Postel *et al*., 1996, p. 787)	0.778	Less than an electric toothbrush consuming 5 kWh
Desalination: Advanced technology, not yet developed (Postel *et al*., 1996, p. 787)	7.78	Video cassette recorder
Desalination: Best present-day technology (Postel *et al*., 1996, p. 787)	23.3	Personal computer
AWVP theoretical minimum energy required to condense water vapour	681	Colour television or clothes dryer

vapour into liquid (2450 J/ml) limits AWVPs use for irrigation to coastal locations with access to seawater coolant for the condensation process. Energy requirements for desalination and AWVP are contrasted in Table 1. Desalination, in theory, requires less than 1 KWh to remove salt ions from seawater to produce 1 m^3 of freshwater. In practice, about 23 kWh are needed. AWVP consumes, in theory, 681 kWh to condense water vapour out of air to produce 1 m^3 of liquid water. But by using natural heat sinks such as the atmosphere and deep cold seawater, AWVP performance can be leveraged so that in the case of seawater coolant it is more productive than desalination in terms of energy input per unit volume of product water. Table 2 shows Rajvanshi's condenser array and Paton's Seawater Greenhouse require 2% and 1%, respectively, of the theoretical minimum energy required to condense water vapour. AWVP using refrigeration technology requires 40–73% of the theoretical minimum, using the atmosphere as heat sink. Other natural heat sinks are radiative cooling into the sky and the subterranean temperature profile. High energy cost of refrigeration technology for surface cooling (Table 2) can be justified if no other safe water supply is available. Efficient, specialized forms of agriculture and horticulture using hydroponic methods with daily water requirements of 0.25–1.25 l m^{-2} (Mason, 1990, p. 18) may be viable with AWVP. Desiccant-based AWVP uses physicochemical processes to leverage performance.

AWVP addresses inadequate rural potable water supplies. Gleick (1998, Table 5) presented vividly inequities between urban and rural water supplies. John Gould, writing about Botswana (Gould, 1997, p. 13), pinpointed the roots of this problem: "Most of the effort and resources for improving water supplies has been directed to the rapidly growing urban areas, and larger villages with populations of 500 and above. Smaller settlements and remote homesteads are difficult and costly to service with conventional technologies ..." This is a concise statement of AWVPs niche. Applications with recommended minimum water-quantity requirements are suggested in Table 3. For urban areas with thousands or millions of people lacking safe water, think then in terms of affordable, bite-sized neighbourhood projects to achieve long-term goals of serving the potable water needs of an entire city.

AWVP can be observed every day. Dew conden-

Table 2. Total system energy, for **desalination** compared to various AWVP systems, required to produce 1 m^3 of fresh water

Method	Energy (kWh/m^3)	Proportion of minimum theoretical energy required (%)	Major energy use
AWVP: Seawater Greenhouse system (Paton and Davies, 1996)	2.6–6.3	0.4–0.9	Pumps and fans
AWVP: Condenser array cooled by deep cold seawater (Rajvanshi, 1981, p. 304)	15	2	Pumping seawater through system
Desalination (reverse osmosis) (Rajvanshi, 1981, p. 304)	**17**	**2185**[a]	**Pumping plus pressurizing feed water to 5400–6800 kPa (UN, 1985, p. 248)**
Desalination (multi-stage flash) (Rajvanshi, 1981, p. 304)	**83**	**10,668**[a]	**Seawater pumping plus heating of feed water (United Nations, 1985)**
AWVP: Refrigerating compressor (Harrison, 1996, 1998)	270–550	40–81	Fan, refrigerant compressor, water pump
AWVP: Refrigerating compressor (Meytsar, 1997)	322	47	Fan, refrigerant compressor, pump
AWVP: Refrigerating compressor (Kajiyama, 1974)	400	59	Fan, refrigerant compressor, water pump
AWVP: Refrigerating compressor The Rainmaker® (ADS, 1999)	480	70	Refrigerant compressor and fan
AWVP: Dehumidification technology (Hellström, 1969, p. 13)	500	73	Refrigerant compressor and fan
AWVP: Condensation by direct expansion of cooled compressed air (Meytsar, 1997)	1800	264	Air compressor, turbine, refrigerant compressor

[a] Proportion is with respect to 0.778 kWh/m^3; other values in column are with respect to 681 kWh/m^3 (Table 1).

sing on cold drink glasses, water dripping from air conditioners, dehumidification systems, and water collecting in air compressors are forms of AWVP that technology can improve to provide new potable water sources. AWVP is precipitation enhancement, precipitating extra water vapour out of the atmosphere.

AWVP IN ACTION: THE SEAWATER GREENHOUSE PROTOTYPE

One substantial operational prototype has been publicized (Coghlan, 1993; Paton, 1995; Booker, 1996; Paton and Davies, 1996, 1997; Pearce, 1998). The £2 million Seawater Greenhouse produced 3000 l daily (*Tomorrow's World* televison program (UK), Water, Water, Everywhere, circa 1995) and operated successfully during the mid-1990s in Tenerife. Funding ended 1995 but data was obtained for future designs. The greenhouse building faced the prevailing northeast wind. Moist air passed through two seawater evaporators (curtains of surface seawater), one at each end of the greenhouse, which washed air and increased its absolute humidity to saturation. Saturated air contacted condenser pipes at the building's leeward end. Fresh water condensed on the pipes which had been chilled below the dewpoint. In the prototype, a heat pump simulated deep cold seawater coolant. Condensate collected in a reservoir and irrigated greenhouse crops of salad vegetables and ornamental plants. The design also captured water vapour transpired by plants in the greenhouse to maximize water collection efficiency. Light Works Limited, project coordinator, claimed, "the capital and operating costs compete favourably with conventional desalination techniques which are generally too expensive to contemplate for agriculture. Most significantly, the electrical energy required to produce both cool air and fresh water is substantially less than for *any* conventional system and may be provided *entirely* by renewable energy." Table 2 highlights the remarkable performance of the Seawater Greenhouse system. Capital cost estimates ranged from £85,000 for a 8000 l/d installation to £1,950,000 for a 550,000 l/d facility (A. C. Paton, 1999, personal communication). Detailed information about the Seawater Greenhouse remains proprietary, but operating and maintenance costs, including staff, should be comparable to those associated with any commercial greenhouse operation.

The Design Sense award, worth £40,000, sponsored by Corus (international multi-metals group) and supported by the Rufford Foundation, was awarded to A. C. Paton in 1999 for his Seawater Greenhouse design. The award recognizes designs and architecture that use natural resources fairly and efficiently in sustainable processes (Design Museum, 1999).

PRINCIPLES

Water vapour molecules are present in every cubic metre of the atmosphere. Unassociated, single water molecules or monomers are known as water vapour. Water vapour density or absolute humidity at a specific location varies with geographical location, altitude, time of day, and season. Density is usually highest near Earth's surface, close to sources of vapour like water bodies and vegetation. By volume, water vapour is 4% of the atmospheric gas mixture, and by mass it is 3% of the air (Barry and Chorley, 1971, p. 22). Horizontal transport of water vapour is enormous. Arid zones may have high absolute humidity even though natural condensation mechanisms may not cause precipitation. AWVP can extract this otherwise unobtainable moisture.

Defining water vapour content of a moist air volume

Absolute humidity or water vapour density is defined (ASHRAE, 1993, p. 6.8) as

$$d_v = M_w/V \text{ (kg m}^{-3}\text{)}, \qquad (1)$$

where M_w is mass of water vapour (kg) and V is total volume of a moist air sample (m^3).

Although ideal for visualizing water quantity extracted from each cubic metre of air flowing through an AWVP site, d_v is little used in meteorology or dehumidification engineering because it is a volumetric measure whose value varies with press-

Table 3. Niche applications for AWVP (based on recommended minimum water-quantity requirements in House *et al*., 1997)

Application	Water usage (l/head/d) unless otherwise stated
Individuals	15–25
Schools	15–30 l/pupil/d
Hospitals (with laundry facilities)	220–300 l/bed/d
Clinics	Out-patients 5; In-patients 40–60
Mosques	25–40
Pour-flush latrines	1–2 l per flush; 20–30 l/cubicle/d
Dry latrines (for cleaning)	2 l/cubicle/d
Livestock: large (cattle)	20–35
Livestock: small (sheep, pigs)	10–25

Table 4. Density, ρ_a of dry air at temperature, t_a and pressure, p = 100 kPa[a]

Temperature, t_a (°C)	Density, ρ_a (kg/m^3)
0	1.28
10	1.23
20	1.19
30	1.15
40	1.11

[a] Data from Ludlam (1980, Table 2.12).

ure. Relative humidity, ϕ, is a temperature dependent measure because as air temperature, t_a, increases, the air's water holding capacity increases. This makes AWVP well-matched as an alternative water source in water-scarce locations which have relatively high average air temperatures.

Absolute humidity at a site is determined using a sea level psychrometric chart (ASHRAE 1993, p. 6.11) if t_a and ϕ are known. The chart shows the corresponding humidity ratio, W, which can be converted to d_v using

$$d_v = W\rho_a \text{ (kg m}^{-3}\text{)} \tag{2}$$

where density of dry air, ρ_a, is found in Table 4.

Collecting water molecules

Processing atmospheric water vapour into drinking water requires two steps. First, water vapour molecules are attracted to a limited volume within a container or to a surface connected to a water storage tank. A vapour pressure gradient is established so there is water vapour flux from the air to container interior or the surface. This is flux of mass (water vapour molecules themselves) and energy (latent heat contained in the gas phase of water molecules). A cooled surface, desiccants, or convection with adiabatic cooling can all create water vapour pressure gradients that concentrate water vapour molecules onto a surface or into a closed volume. These three methods are described in the "AWVP types" section.

Building liquid water

The second step associates or joins individual water vapour molecules, H_2O, by hydrogen bonds

Table 5. Designs for atmospheric water vapour processors

Design type	Reference	Output (l/d)	Output (measured, hypothetical)
1. Cooled surface			
Heat pump	ADS (1999), The Rainmaker®	25	Measured
	Balezov and Minev (1997)	n.a.	
	Engel and Clasby (1993)	n.a.	
	Frick (1978a)	n.a.	
	Frick (1978b)	n.a.	
	Gerard and Worzel (1967, 1972)	3,790,000	Hypothetical
	Harrison (1996, 1998)	9–18	Measured
	Hellström (1969)	50–170	Measured
	Kajiyama (1974)	12	Measured
	Karniel (1994)	n.a.	
	Kückens (1983)	n.a.	
	Meytsar (1997)	4275	Hypothetical
	Michael (1996)	n.a.	
	Nasser and Pocrnja (1980)	n.a.	
	Paton and Davies (1996)	121,000–500,000	Hypothetical (per ha equivalent)
	Peeters and Berkbigler (1997)	n.a.	
	Poindexter (1994)	11	Measured
	Rajvanshi (1981)	643,000	Hypothetical
	Rosenthal (1999)	4	Measured
	Seymour and Bothman (1984)	5,860,000	Hypothetical
	Steiner (1999)	240,000	Hypothetical
	Swanson (1972)	n.a.	
	Wold (1997)	n.a.	
	Zacherl (1986)	360	Hypothetical
Radiative cooling	Hellström (1969)	3460–4000	Measured (per ha equivalent)
	Nilsson *et al.* (1994)	1200	Measured (per ha equivalent)
	Smith (1983)	5000–20,000	Hypothetical (per ha equivalent)
	Beysens *et al.* (1998)	1000–5000	Measured (per ha equivalent)
2. Desiccant			
Liquid	Clarke (1993)	n.a.	
	Lund (1973)	1.7 million	Hypothetical
Solid	Bennett (1983)	n.a.	
	Elmer and Hyde (1986)	15,500	Measured (per ha equivalent)
	Groth and Hussmann (1979)	1000–100 million	Hypothetical (various versions)
	Kronauer (1996)[a]	n.a.	
	Mitsubishi Electric Corp. (1981)[a]	n.a.	
	Takeyama *et al.* (1982)	n.a.	
	Yamamoto *et al.* (1981)	n.a.	
3. Convection	Carte (1968)	108,000	Measured in mine vent. shaft
	Meytsar (1997)	2376	Hypothetical
	Ockert (1978)	n.a.	
	Starr *et al.* (1972)	(11–22) million	Hypothetical
	Starr *et al.* (1974)	(5–31) million	Hypothetical
	Stolbov (1993)[a]	n.a.	

[a] Abstract only was reviewed. n.a = not available. "Per hectare equivalent" means that information was available in the reference document to normalize water production to a unit area. This table is not an exhaustive listing. Many of the documents contain cross-references to other AWVP designs.

into water polymers or clusters $(H_2O)_c$, where c is number of molecules. Degree of association for water vapour molecules is inversely proportional to temperature. Cooling a volume of moist air decreases kinetic or translational energy of water vapour molecules and probability increases that neighbouring molecules will bond into clusters forming liquid water droplets. Carlon (1984) stated that a near spherical cluster of approximately 45 water vapour molecules exhibits bulk liquid properties.

Beysens (1995) emphasized that during phase change from water vapour to liquid water there is an energy barrier to overcome. The barrier is related to tension at the liquid–vapour interface. For condensation in pure air (homogeneous nucleation) air must be chilled well below the conventional dewpoint. Wetting properties of a substrate reduce the energy barrier considerably, promoting heterogeneous nucleation which produces dew at the dewpoint. By manipulating wetting properties, droplet pattern characteristics can enhance water collection.

Problem of latent heat release

AWVP designs must cope with latent heat or heat of vaporization released whenever water changes phase from gas to liquid. This heat must be dissipated to prevent liquid water from re-evaporating before storage.

A water vapour molecule has total energy partitioned amongst its translational, vibrational, rotational, electronic, and nuclear energies. Only translational and rotational energies concern us here. Translational or kinetic energy transfers water vapour molecule mass between locations. It is proportional to absolute temperature. Gas phase molecules are always in motion but average speed of each molecule decreases as absolute temperature decreases. Slower molecular speeds allow intermolecular forces to act and promote hydrogen bonding.

Internal rotation of the water vapour molecule accounts for energy equal in value to heat of vaporization. When hydrogen bonding occurs between water vapour molecules, the resulting cooperative structure (like a cage, called a clathrate) of the molecule cluster does not permit internal rotation. Rotational energy is rejected and is sensed as translational energy (sensible heat). This is the same quantity of heat that was required to evaporate the

Table 6. Strengths and limitations of AWVP methods

Plus	Minus
Type 1: Cooled surface	
Heat pump	
• Mechanical cooling is a well developed technology used for refrigeration, air conditioning, and dehumidification (Harriman, 1990)	• Cooling process may freeze the condensed vapour.
• Fairly efficient when condenser air temperature is low and cooling coil air temperature is high (Harriman).	• Frost acts as insulator to further cooling.
• Maintenance expertise fairly common.	• Airflow may be reduced when cooling elements are blocked by frost.
	• Special design required for dewpoints less than 4.5°C. (The above four points are from Harriman).
	• Finite size of cooling coil means that all of the air flowing past is not cooled at same rate. There is unavoidable mixing of dried and unprocessed air within the processor (Khalil, 1993).
	• Power requirements fairly high.
	• Conventional refrigeration still uses chlorofluorocarbons (CFCs) which contribute to global high altitude ozone depletion.
Radiative cooling	
• Needs no external energy source.	• Existing technology dependent on radiation into a clear night sky heat sink.
• Simple mechanical requirements.	
Type 2: Desiccants	
• Well-developed technology for large scale dehumidification in industrial settings.	• Energy requirements fairly high for recovering potable water using desalination or distillation technology.
• Can dry air to a low relative humidity.	• Heat of sorbtion is 5–25% of heat of vaporization (ASHRAE, 1993) and must be considered in design.
• Suitable for output air at low dewpoints.	• Liquid absorbents can concentrate contaminants from the atmosphere (ASHRAE). Apart from possible pollution of the product water, contaminants can reduce the capacity of the desiccant.
Type 3: Convection induced or controlled in a structure	
• Adiabatic cooling has lowest energy requirements of the three design strategies.	• Large structure (tower or tube 100s to 1000s of metres long) required.
• Natural precipitation process with extensive body of applicable meteorological theories: orographic precipitation, tornadoes, convection cells.	• No prototypes known to exist other than mine shaft analogy (Carte, 1968).
• Engineering experience in removal of water from industrial compressed air systems is well-developed.	• Not used for dehumidification so engineering knowledge base is limited.
	• AWVP designs which propose compression of air followed by expansion to cause cooling below dewpoint are energy intensive (one embodiment of Meytsar, 1997).

water molecule. In this manner, energy is transferred by water molecules. Condensing 1 ml of liquid water (weighing 1 g) out of air releases energy of 2450 J at 20°C. Compare this energy with a 40 W light bulb which consumes 40 J in 1 s or 2400 J in 1 min.

Recognizing that collecting water molecules, building liquid water polymers, and coping with latent heat release are common to all AWVP devices, it is time to consider three methods that were developed for processing water vapour into liquid water.

AWVP TYPES

Classification of various AWVP designs discussed in the literature and in patents enables understanding the technology for further development and presenting to policy-makers (Fig. 1 and Table 5). Design types include: surface cooling by heat

Table 7. Comparison of surface cooling by heat pump and desiccant technologies[a]

Type 1: Surface cooling by heat pump	Type 2: Desiccants
Establish vapour pressure gradient by cooling air below dewpoint causing water vapour to condense on heat exchanger surface. Refrigeration and air conditioning technology.	Low water vapour pressure at desiccant surface creates vapour pressure gradient which attracts water molecules from the air. Wide range of commercial/industrial uses for drying air at atmospheric pressure. Moisture removal by heating to 50–260°C.
• Direct contact (air washers, cooling towers) • Cooling and dehumidifying coils The lower the temperature, the drier the air becomes.	• Air flow removes moisture • Cool desiccant to start attracting water molecules again. High holding capacity (up to 1100% of dry mass). More desiccant removes more moisture.
Two types	Two types
• Direct expansion of refrigerant gas (for smaller air flows such as residential or commercial rooftop air conditioners). —can cool air to 6–7°C.	• Adsorbents (solids)—water molecules simply added to surface
—difficult to achieve dewpoints below 4.5°C because of uneven cooling of air. Some air near heat exchanger may be cooled below freezing temperature of water.	• Absorbents (liquids)–water molecules incorporated into substance via physical or chemical changes
• Chilled liquid (for larger air flows such as water coolers for commercial/industrial buildings or other large installations), liquid is typically water, glycol, or brine.	Five configurations
—chilled liquid system allows control at low temp. —cool almost to 0°C without freezing condensate —equalizes compressor and condenser loads	• Liquid spray tower—larger installations • Solid packed tower—smaller installations • Rotating horizontal bed • Multiple rotating bed • Rotating desiccant wheel—all installation scales, laminar air flow, lowest energy requirement, use for solids and liquids.
Efficiency highest when • Condenser air temp. is low • Inlet air temperature is high • Air moisture level is high	Most efficient with desiccant having • High moisture capacity • Low mass
Condensate may freeze	Performance best with lower inlet temperatures, inlet air may need pre-cooling
• Heat transfer is reduced • Frost clogs coil, airflow reduced	
Cooling capacity must allow for latent heat conversion to sensible heat.	Preferred method when:
	• "... latent load is large in comparison to sensible load..." (ASHRAE, p. 19.1). Use when absolute humidity is high • Energy cost to regenerate (cool) desiccant is low compared to chilling a surface below the dewpoint • Air dewpoint is below 0°C.
Filtration of inlet air required to keep heat exchanger surfaces clean. Filters need regular replacement.	Filtration of reactivation air required. Filters need regular replacement. • Dust kept out of solid desiccant • Organic vapours kept away from solid desiccant Latent heat causes processed air to be warmer than incoming air. Heat of sorption is 5–25% of latent heat of water. Relatively slow air flow required. Equipment lifetime 15–30 years (Harriman, 1990). Desiccant operating lifetime 10,000–100,000 h.
May need frost melting cycle (no dehumidification occurs).	Design must allow for operation of desiccant cycle (Table 11).
Efficiency is defined by the coefficient of performance, C_P. $C_\mathrm{p} = \frac{\text{energy removed from airstream}}{\text{energy invested in compressor and fans}}$	Desiccants are one type of sorbent which are particularly useful for attracting water molecules. Desiccant may also attract unwanted molecules (pollutants, contaminants, organic vapours, microbes). Although this trait can be exploited in dehumidification it is undesirable for AWVP for potable water.
Typical C_P is 2.0–4.5	

[a] Based on information in Harriman (1990) and ASHRAE (1993).

pumps or radiative cooling, water vapour concentrators using desiccants, and convection induced or controlled in a structure. These are compared in Table 6.

Surface cooling by heat pumps or radiative cooling

Heat pumps. This method in the Seawater Greenhouse produced 3000 l of fresh water daily. Advanced Dryer Systems, Inc. (ADS) of Florida has used heat pipe technology, developed for the American space program by inventor Khanh Dinh, in The Rainmaker® which, with an airflow of 0.1 m^3 s^{-1} (Johnson, 1999a), can produce 25 l of water/day when air temperature is 27°C and relative humidity is 60% (absolute humidity, $d_v = 15.7$ g m^{-3}). Chlorodifluoromethane is used as refrigerant in the 38 × 33 × 54 cm machine weighing 27.5 kg which has a coefficient of performance of 3.2, consuming 480 kWh to extract 1 m^3 of fresh water from the atmosphere (ADS, 1999). Recognizing the trend to minimize the use of fluorocarbon-based refrigerants, Peeters and Berkbigler (1997) and Wold (1997) used thermo-electric (Peltier) heat pumps. Table 7 compares surface cooling to desiccant methods. The energy and mass cascade of a heat pump based water vapour processor is shown in Fig. 2. Heat pumps are used to cool surfaces so water vapour can condense and be collected.

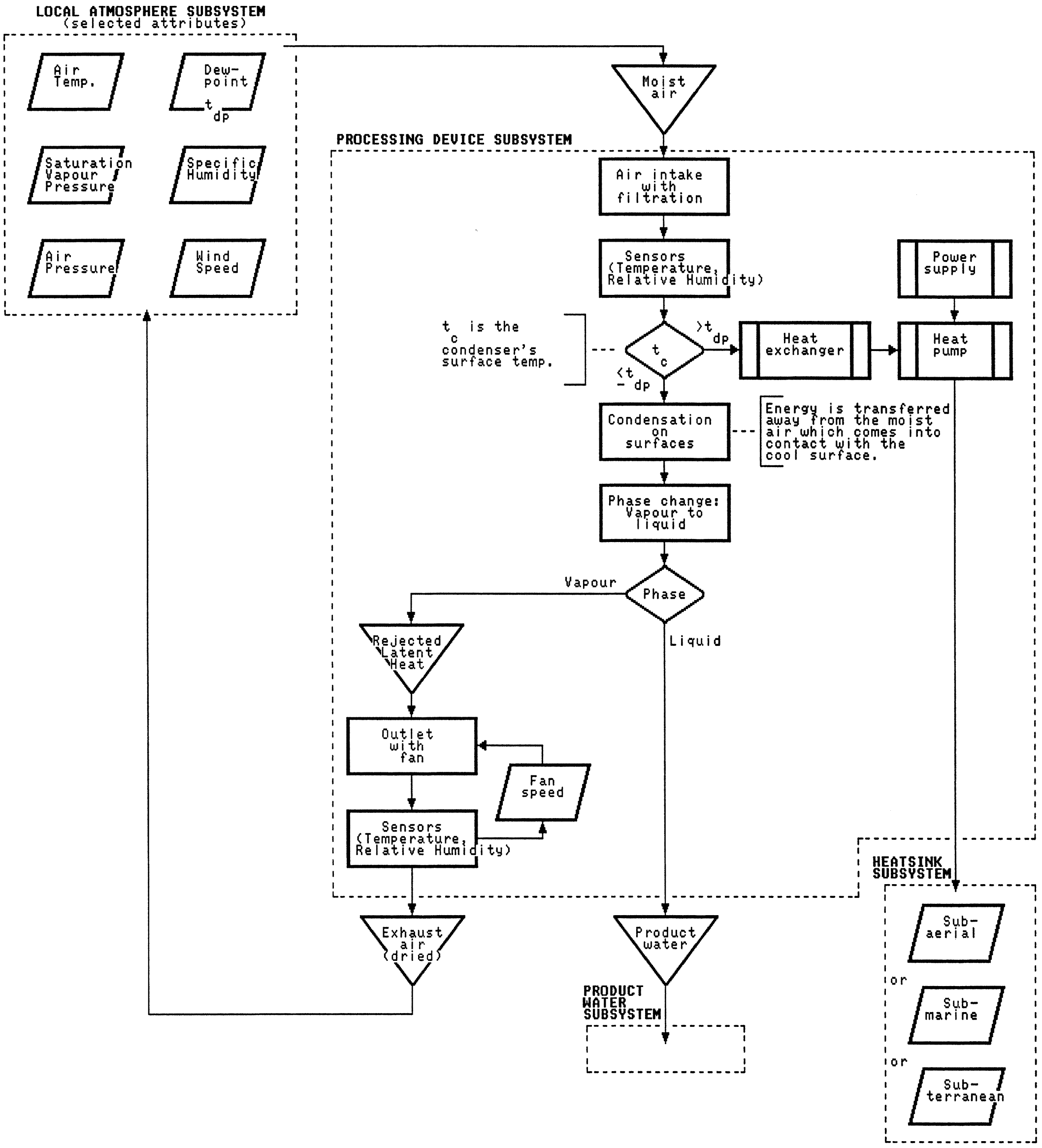

Fig. 2. Design type 1—Heat pump based system for condensing atmospheric water vapour shown as an energy and mass cascade.

This approach is subdivided into three categories depending on the heat sink used. Those systems transporting a critical amount of energy from the cooled surface into ambient air are using a subaerial heat sink (Hellström, 1969; Swanson, 1972; Kajiyama, 1974; Frick, 1978a; Nasser and Pocrnja, 1980; Zacherl, 1986; Engel and Clasby, 1993; Poindexter, 1994; Karniel, 1994; Harrison, 1996; Michael, 1996; Balezov and Minev, 1997; Meytsar, 1997; Peeters and Berkbigler, 1997; Wold, 1997; Rosenthal, 1999; Steiner, 1999). A submarine heat sink is used by systems depending on deep cold ocean water for cooling (Gerard and Worzel, 1967, 1972; Frick, 1978b; Rajvanshi, 1981; Seymour and Bothman, 1984; Paton and Davies, 1996). Only one case of an underground or subterranean heat sink was found (Kückens, 1983).

Energy (sensible heat) is transferred away from moist air flowing past the cooled surface of the atmospheric water vapour processor. Air cooling rate is governed by temperature differences between condenser surfaces and air (Khalil, 1993). Latent energy flux results when water molecules change phase from vapour to liquid. Latent heat passing to the air parcel being processed is proportional to amount of water vapour condensed. Processor cool-

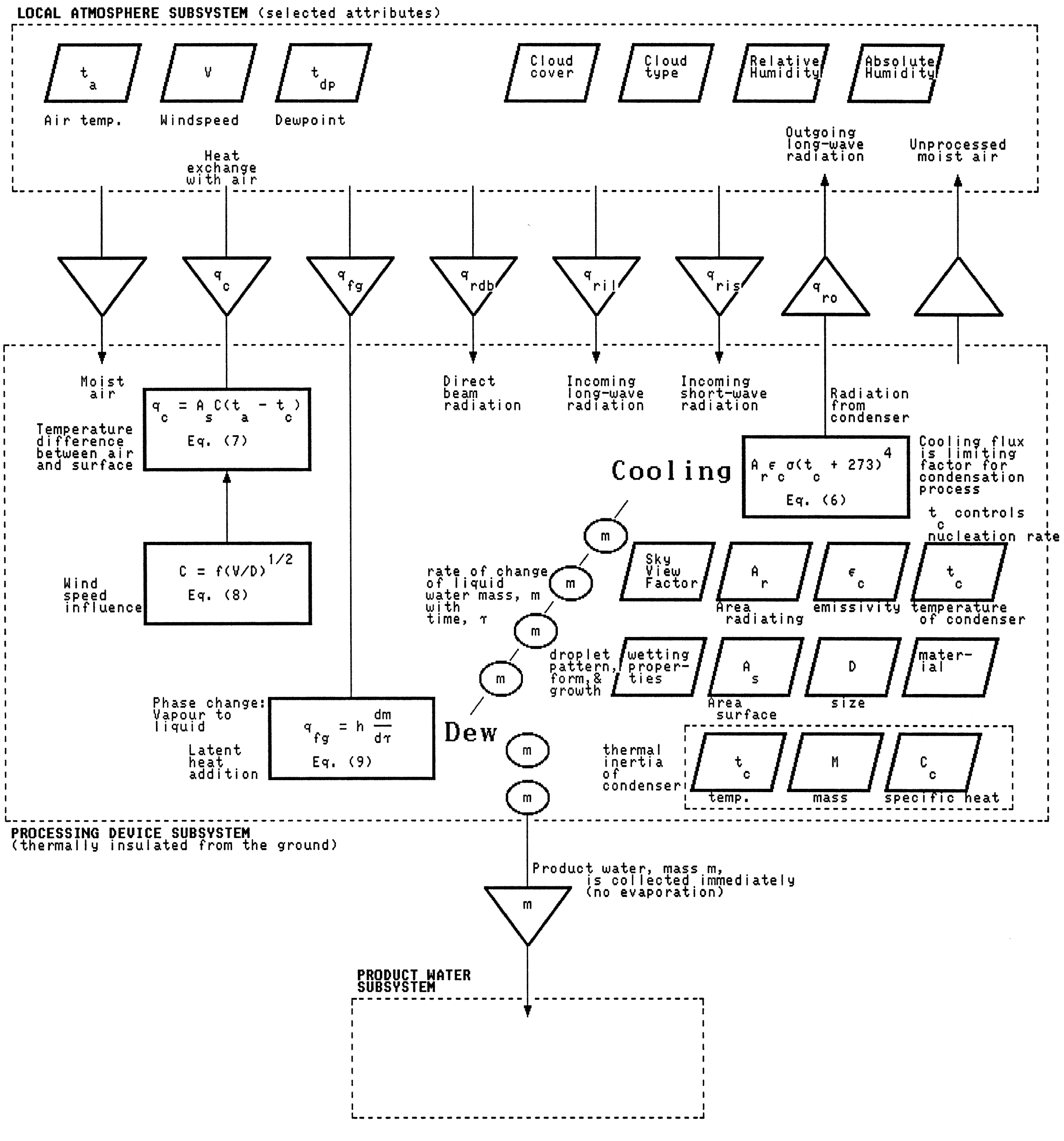

Fig. 3. Design type 1—Radiative cooling system for condensing atmospheric water vapour depicted as an energy and mass cascade.

ing capacity must take this heat into account so newly condensed water is not evaporated.

Efficient water vapour processing using a heat pump system maximizes the ratio

$$n = Q_L/(Q_L + Q_s), \tag{3}$$

where Q_L is latent heat, Q_s is sensible heat and $(Q_L + Q_s)$ is enthalpy, or total energy of an air parcel at constant pressure (Seymour and Bothman, 1984). Maximizing n requires sensing temperature and humidity. Feedback from sensors adjusts airflow and cooling rate to cool incoming moist air, minimizing Q_s. There is no benefit in further cooling the *flowing* air after it is saturated and condensation starts collecting on the cooled surface. Additional energy for cooling is wasted converting latent heat to sensible heat that would be carried away in the airstream. This is unlike *still* air, for which deeper cooling below the dewpoint reduces water holding capacity and wrings out additional moisture with each degree drop in temperature.

Radiative cooling. Eliminating energy costs for cooling surfaces below the dewpoint is possible. AWVP techniques using radiative cooling to lower surface temperature below the dewpoint of adjacent air (Fig. 3) are described by Hellström (1969), Smith (1983), Nilsson *et al.* (1994), Beysens (1995), Nikolayev *et al.* (1996), and Beysens *et al.* (1998). Nilsson and co-authors were researchers at Swedish

Table 8. Comparison of adsorbent and absorbent desiccant technologies[a]

Adsorbents	Absorbents
Solids	Liquids
At given temp., solid surface vap. pressure lower than ambient air.	At given temp., liquid has vap. pressure lower than ambient air.
Simpler system. Relatively inexpensive.	More complex system, therefore expensive.
Usually for smaller spaces, free standing units.	Usually large central system.
Solid packed tower type often used for compressed air.	Used at atmospheric pressure.
Low dewpoints (−40°C)	
Use for "… very small, low dewpoint airstreams". (Harriman, 1990).	
Can dehumidify warm airstreams without loss of efficiency.	Warm airstreams decrease dehumidification efficiency.
Molecular sieve adsorbents can be manufactured to only adsorb water molecules (diameter 3.2 nm). Therefore can eliminate organic solvent molecules.	May be contaminated by organic solvents.
Disadvantages:	Disadvantages
• leakage of air between wet and dry airstreams	• response time (long pipes, reserve sump)
• high reactivation energy (and operating cost if energy is expensive)	• maintenance—liquid desiccants are corrosive so improper operation such as too high an air velocity which suspends droplets of desiccant in airstream can corrode machine. At low humidity, desiccant can dry out quickly
	• relatively high capital cost for smaller units
Packed tower needs to be large to allow for low air velocity because proper operation needs:	
• even flow throughout packed desiccant	
• protection of desiccant from lifting and shattering	
Initial deep drying but as desiccant fills up air is not dried as much.	
Rotating horizontal bed has higher air flow in a compact space.	
At same t_a and ϕ has lower capacity than absorbent.	At same t_a and ϕ has higher capacity than adsorbent.
Adsorption $= f$ (total surface area, total capillary volume, range of capillary diameters). Implications/tradeoffs are:	Vapour pressure, $p_w = f(t$, 1/concentration of desiccant). Implications of this are:
• if total surface area is large, have higher capacity at low ϕ	• as desiccant temperature, t, increases, fewer water molecules are attracted from the air. This could be disadvantageous in hot climates unless additional energy is expended on cooling the desiccant. Alternatively, a higher concentration desiccant solution can be used but this also has a cost.
• large capillaries give higher capacity at high ϕ	• higher concentration allows air to be dried to a greater degree.
• can combine adsorbents to give satisfactory operation across a wide range of conditions	
Form:	Maximize water molecule absorption by:
High surface area to mass ratio (e.g. >4600 m^2/g) like a rigid sponge.	• increasing surface area exposed to air
	• increasing contact time
Function:	
• water condensed into desiccant capillaries—moisture attracted by electrical field at desiccant surface, force field not uniform	LiCl with air at 90% RH, equilibrium
• single water molecules held within crystalline structure of desiccant material	26 water molecules/LiCl molecule or 1000% of dry mass. Achieve this by:
• complete surface covered with water molecules	• spraying desiccant into air (like cooling tower)
• vapour condenses into first water layer—capillaries are filled throughout desiccant	• "… rotating extended surface …" (ASHRAE, 1993, p. 19.4)
Operating life up to 100,000 h.	Operating life up to 100,000 h.
Loss of capacity by contaminants, clogging by dust and organic vapours, hydrothermal stress (due to expansion/contraction).	Loss of capacity by contaminants reacting chemically with the desiccant solution causing its properties to change.

[a] Based on information in Harriman (1990) and ASHRAE (1993). t_a is air temperature, ϕ is relative humidity.

Table 9. Adsorbent classes (after ASHRAE, 1993, pp. 19.4–19.5)

Class	Properties
Silica gels	Low cost, easy to customize for selective adsorption. Physically, these range from fine powder to beads about 5 mm diameter.
Zeolites	Aluminosilicates, naturally occurring, open crystalline lattice functions as sieve.
Molecular sieves (synthetic zeolites)	Higher cost than natural zeolites but have uniform structure.
Activated aluminas	Manufactured for specific structural characteristics.
Carbons	High capacity for water molecules at $\phi = 45$–100%, easily adsorb organic solvents.
Synthetic polymers	Highest capacity of adsorbents. This is a relatively new technology with potential as a desiccant (e.g. polystyrenesulfonic acid sodium salt, PSSASS).

universities while Nikolayev, Beysens and colleagues worked at Département de Recherche Fondamenatale sur la Matière Condensée in Grenoble, France making significant advances in understanding radiative cooling, dew formation and application of these processes to water supply devices.

Condenser Heat Transfer Balance Equation

This is fundamental to dew collector designs. Change in heat of the radiator/condenser surface on the left-hand side of the equation balances the right-hand side heat transferred to or from the condenser surface by various physical processes so that

$$\frac{dt_c}{d\tau}(Mc_c + mc_w) = q_{rt} + q_c + q_{fg} \tag{4}$$

where t_c is condenser temperature (°C), τ is time (s), M is condenser mass (kg), m is condensed water mass (kg), c_c is condenser material specific heat (J kg^{-1} K^{-1}), and c_w is liquid water specific heat (4180 J kg^{-1} K^{-1}).

On the right-hand side, three terms represent various forms of radiative heat transfer per unit time (W). Total time rate of heat transfer is denoted by q_{rt}, q_c is heat exchange with air, and q_{fg} is power gain from latent heat converted to sensible heat. The three right-hand side terms can be defined in detail. Thus

$$q_{rt} = q_{rdb} + q_{ril} + q_{ris} - q_{ro} \tag{5}$$

where q_{rdb} is direct beam radiation, q_{ril} is long-wave diffuse incoming radiation, q_{ris} is short-wave diffuse incoming radiation, and q_{ro} is outgoing radiation of the condenser. Models for estimating q_{rdb}, q_{ril}, and q_{ris} are in Nikolayev *et al.* (1996). The radiation from the condenser, q_{ro} which is key to providing a cooled surface for condensation of dew, is

$$q_{ro} = A_r \epsilon_c \sigma (t_c + 273)^4 \tag{6}$$

where A_r is radiating surface area (m^2) of the condenser, σ is the Stefan–Boltzmann constant (5.67 10^{-8} W m^{-2} K^{-4}) and ϵ_c is condenser emissivity.

Heat exchange by convection and conduction between condenser and air is

$$q_c = A_s C(t_a - t_c) \tag{7}$$

where A_s is condenser surface area from which heat exchange occurs, C is a heat transfer coefficient, and t_a is air temperature. Influence of air flow across the surface on amount of condensation that is produced on the radiator/condenser is accounted for in the model by the coefficient

$$C = f\sqrt{V/D}\ (\mathrm{W\ K^{-1}\ m^{-2}}) \tag{8}$$

where V (m s^{-1}) is air velocity and $f = 4$ (W K^{-1} m^{-2} s$^{1/2}$) is an empirical factor for flow parallel to a plane with size D (m).

Time rate of heat transfer attributable to enthalpy of vapourization (latent heat of condensation) of water is represented by

$$q_{fg} = h\frac{dm}{d\tau} \tag{9}$$

where h is enthalpy of vapourization of water (2.26 × 10^6 J kg^{-1}) and dm/dτ represents condensation rate. This is non-zero only if $p_w > p_{ws}(t_c)$ where p_w is water vapour partial pressure and $p_{ws}(t_c)$ is vapour pressure at the condenser surface when condensation begins. A vapour pressure gradient must exist for water molecules to flow from the air to the cooled surface where newly condensed water droplets are collected.

Dew collection continuously throughout night *and day* is the goal of the Swedish and French researchers. They are zeroing in on low-mass foils, such as polyethylene pigmented with ZnS, which is both an efficient reflector of short-wave and emitter of long-wave radiation. Condensation occurs on both sides of the sheet and degree of inclination has minimal influence on yield, expected through simu-

Table 10. Ranking of sorption characteristics for relative humidity, $\phi > 50\%$ and air temperature, $t_a = 22$°C (after ASHRAE, 1993, chap. 19, Fig. 7). Best performance is ranked number 1

Adsorbents	Absorbents
1. PSSASS	1. LiCl (100% at $\phi = 90\%$)
2. Slica gel	2. Triethylene glycol (98% at $\phi = 90\%$)
3. Activated carbon	
4. Activated alumina	
5. Molecular sieve	

lations to be 1 l m^{-2}, where unit area is one side of the sheet (Nikolayev *et al.*, 1996, p. 32).

Interestingly, the condenser heat balance equation is applicable also to surfaces cooled by heat pumps. Substitute net total time rate of heat transfer from the heat pump for q_{rt} in equation (4).

Water vapour concentrators using desiccants

Desiccants acting as water vapour concentrators extract water vapour from air by establishing a vapour pressure gradient causing flow of water molecules toward the desiccant surface. Desiccants that do not change chemically or physically when water vapour is added are called *adsorbents*. In contrast, *absorbents* undergo chemical or physical changes when they absorb water. Usually, adsorbents are solids while absorbents are liquids. Some patent documents predicted that daily fresh water production from desiccant AWVP technology would be millions of l. Two types of desiccant technology are compared in Table 8.

Solid desiccant technology uses materials having large internal surface area per unit mass, for example, 4600 m^2 g^{-1} (ASHRAE, 1993). Water vapour molecules are attracted to the desiccant surface electrical field and condense inside capillaries.

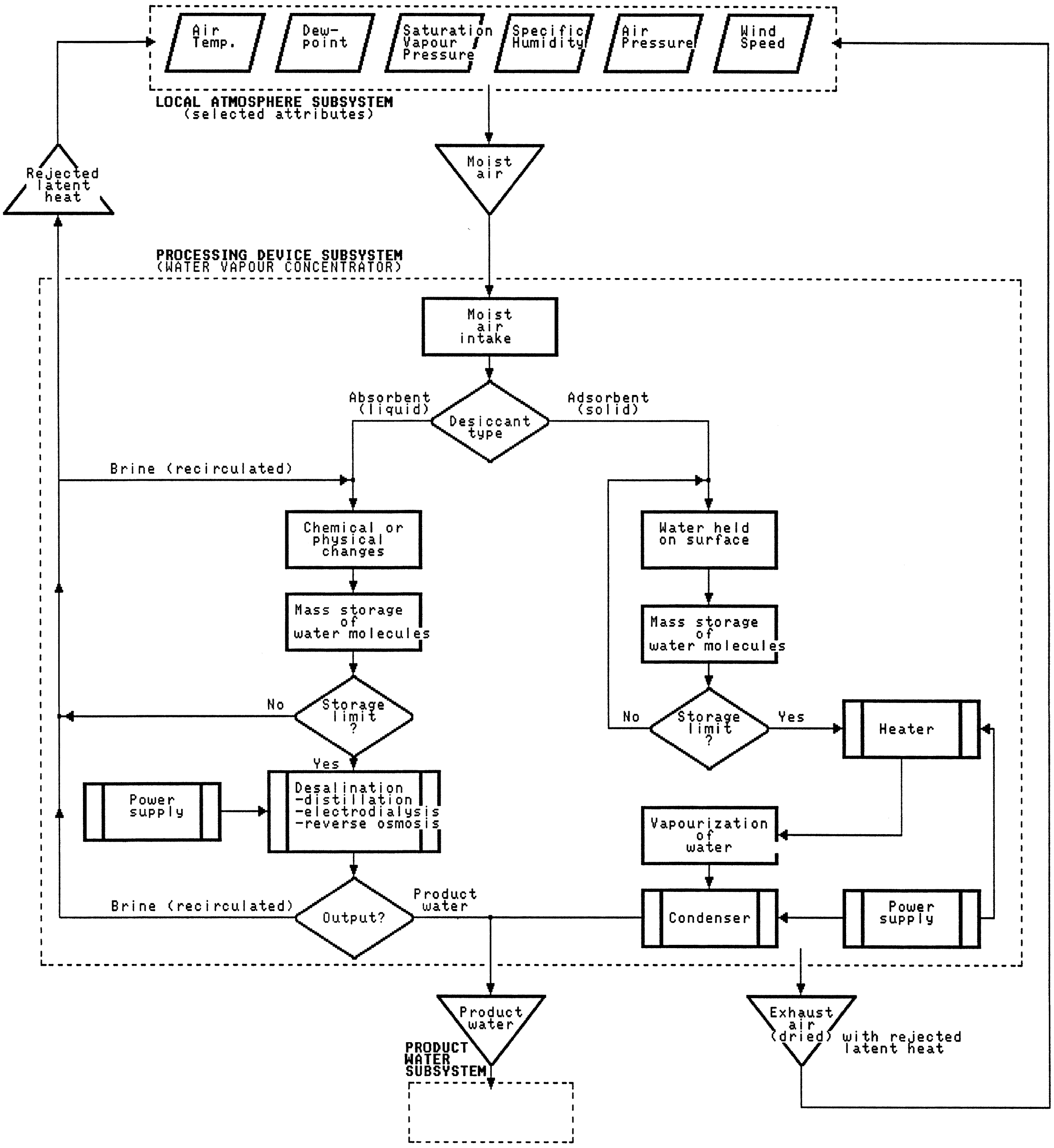

Fig. 4. Design type 2—Desiccant (liquid or solid) systems for atmospheric water vapour processing presented as an energy and mass cascade.

Heaters force collected water molecules out of the adsorbent. Heated, moisture rich air flows past refrigerated surfaces to condense water vapour. Takeyama *et al.* (1982) as well as Elmer and Hyde (1986) suggested hydrated salts coating various inert carriers are effective water vapour adsorbents. Elmer and Hyde concluded that, "Desiccant by itself is less effective as a moisture getter than when supported on a carrier". They found adsorption rate increases linearly with relative humidity. Actual atmospheric water recovery, using a sand/calcium chloride mixture, was 15.5 m^3 day^{-1} ha^{-1}.

Silica gel is adsorbent of choice for Groth and Hussmann (1979), Yamamoto *et al.* (1981), one version of the invention of Takeyama *et al.* (1982), and Bennett (1983). Properties of various adsorbents are listed in Table 9.

Liquid desiccants are a different case. Water vapour is attracted by the vapour pressure gradient and changes phase upon absorption by the liquid. Desalination techniques such as distillation, electrodialysis, or reverse osmosis separate liquid water from liquid desiccant as specified by Lund (1973) who designed and patented a water vapour processor using an 80% solution of lithium chloride in water as absorbent. Clarke (1993) used triethylene glycol as liquid desiccant and solar distillation techniques for desorption. Sorption characteristics of adsorbents and absorbents are ranked in Table 10.

The energy and mass cascade for desiccant based strategies is shown in Fig. 4. A three-step desiccant cycle applies to both liquid and solid sorbents (Table 11). Performance of desiccant dehumidifiers is expressed in AWVP terms in Table 12.

Inducing and controlling convection in a structure

Another way of lowering air temperature below the dewpoint is to cause air parcels to expand, transforming a portion of their energy into work, cooling air to extract liquid water.

Convection based water vapour processors were championed by Starr *et al.* (1972, 1974). Figure 5 shows the energy and mass cascade. These processors contain a convection cell of moist air inside a vertical tube or tower which may extend 100s or 1000s of metres up into the atmosphere (structural engineering for these designs is a challenge). Moist adiabatic cooling occurs as the cell expands in volume when forced upwards into a zone of lower air pressure by induced convection. Condensation and precipitation occur within the column when the temperature of the convection cell drops below the dewpoint.

APPLICATIONS TO REGIONS OF WATER SCARCITY

The natural range of absolute humidity is from 4 to 22 g of water per cubic metre of moist air with many population centres having values between 5 and 10 g per cubic metre. Absolute humidity (meteorological normals) in regions of low precipitation (annual average 300 mm or less) ranges from 4.0 g water vapour per cubic metre of surface air in the atmosphere (Las Vegas, Nevada, USA) to 21.2 g m^{-3} (Djibouti, Republic of Djibouti). Antofagasta, Chile has normal absolute humidity of 10.9 g m^{-3}. These data are from Hellström (1969, Table 1 and Appendix 1). Potential water production rate (in l/d) is

$$\begin{aligned}&\text{Daily water volume (l day}^{-1}\text{)}\\&\quad = \text{Airflow (m}^3\ \text{s}^{-1}\text{)} \times 86{,}400\ \text{s day}^{-1}\\&\quad \times \text{Absolute humidity (g m}^{-3}\text{)} \times 1/1000\ \text{l g}^{-1} \times \eta.\end{aligned} \tag{10}$$

Table 11. Desiccant cycle summary with reference to AWVP[a]

Stage	Process	
1.	Water sorption	Vapour pressure gradient causes water molecules to leave airstream and enter desiccant. Latent heat is converted to sensible heat, warming the airstream.
2.	Desiccant reactivation or regeneration	Vapour pressure gradient between air and desiccant has declined to zero. It is time to drive the moisture out of the desiccant by heating it to as high as 120°C. This reverses the vapour pressure gradient so that water molecules leave the desiccant and enter the lower vapour pressure scavenging airstream that picks up the water molecules. In an AWVP device, especially if using solid desiccants, this airstream must be cooled later to cause the water vapour to condense so that liquid water can be collected and stored (Fig. 4). For a liquid desiccant device it is possible that the water could be separated from the brine by desalination techniques. Regeneration energy = energy required to raise desiccant temperature so that vapour pressure gradient is reversed + energy needed to evaporate water in desiccant + energy associated with desorption of water from the desiccant.
3.	Desiccant cooling	Cooling of the desiccant itself must occur so that the original water vapour gradient is reestablished to begin a new cycle of water molecule collection at Stage 1. Typical cooling might be from 120°C to 10°C. Cooling energy = *f*(desiccant mass, difference between maximum reactivation temperature and Stage 1 starting temperature)

[a] From information in ASHRAE, 1993, chap. 19 and Harriman, 1990, chap. 3.

The definition of efficiency, η, is that of Hellström (1969, p. 11):

$$\eta = \frac{\text{Amount of water extracted per unit time}}{\text{Total moisture content of air processed per unit time}} \qquad (11)$$

Equation (10) establishes suitability of any water vapour processing machine for a given purpose in a specific location. Consider two different scenarios involving locations in Chile and Kenya. Information from 1994 (Gleick, 1998, Table 5) reveals that 94% of the urban population in Chile has access to safe drinking water, but only 37% of the rural population enjoys this access. In Kenya, 67% of the urban and 49% of the rural population has safe drinking water.

A 40% efficient machine in the rural surroundings of Antofagasta (absolute humidity 10.9 g m^{-3}) with airflow of 10 m^3 s^{-1} would produce 3767 l

Table 12. Variables affecting performance of desiccant dehumidifiers (after Harriman, 1990, pp. 6-2 to 6-10) and AWVP analogs to these variables

	Desiccant dehumidifier variables		AWVP desiccant variables
1.	Process air moisture.	1.	Ambient (outdoor) air moisture.
2.	Process air temperature. • lower inlet temperatures enhance water extraction. • higher inlet temperatures reduce performance.	2.	Outdoor air temperature. • inlet temperature may have diurnal and seasonal variation which must be accounted for in the system design and water output specifications.
3.	Process air velocity through desiccant (2–3 m/s). • more water is extracted at low velocities but this efficiency must be traded off against need for larger equipment for slower airflow. • if process air has a high moisture content the performance gain for slower airflow with larger equipment may not be cost effective. • higher velocities result in higher moisture removal rate.	3.	Natural wind velocity through desiccant or fan assisted to 2–3 m/s. • focus is on maximizing moisture removal rate—therefore bias is fortuitously towards smaller and less equipment. expensive
4.	Reactivation air temperature. • heating desiccant causes it to release moisture. • heater capacity may need to be increased in cooler weather to maintain performance level.	4.	Outdoor air temperature will often be lower than in commercial/industrial applications so that a larger desiccant unit would be required for AWVP unless additional energy is input for regeneration of the desiccant. For efficiency, the desiccant should be as dry as possible when re-exposed to the process airstream.
5.	Reactivation air moisture. • usually design for minimum moisture content of inlet reactivation air and to prevent leakage of moisture from reactivation to process side.	5.	Outdoor air moisture content at an AWVP site would usually be relatively high so moisture of air entering reactivation would be higher than optimum for standard dehumidification applications—therefore a relatively high reactivation temperature may be required.
6.	Reactivation air velocity through desiccant (1–3 m/s) • ***reactivation air is simply expelled to the atmosphere with no attempt made to condense the water molecules that were collected.***	6.	Air velocity through desiccant: • set airstream at *minimum* required to transport heat to desiccant, to optimize energy consumption of subsequent condensation process.
7.	Surface area or volume of desiccant exposed to reactivation and process airstreams. • moisture removal rate is a function of amount of desiccant. • air friction increases with surface area exposed to airstream. • both granular and liquid desiccants promote turbulent flow which sets up the condition that airflow resistance increases as square of air velocity. • some designs promote laminar flow but even so resistance is proportional to desiccant bed depth. • general principle is to ensure that energy consumption vs air moisture removal capacity is optimized.	7.	Same as for dehumidifier
8.	Desiccant sorption/desorption characteristics. • designers may combine two or more desiccants in same unit to increase range of temperature and humidity conditions for use of the equipment. • solid adsorbent performance degrades over time as surfaces and crevices fill with atmospheric dust that bypasses filtration. Organic vapours can alter desiccant surfaces. • liquid absorbents may change chemically over the years with exposure to chemical pollutants in the air that is being processed to capture water molecules.	8.	Customize desiccant combinations to climatic conditions (air temperature and absolute humidity) at the site. Plan for periodic replacement of desiccants.

water per day. At a modest consumption of 50 l per person per day, 75 people could have their domestic water requirements satisfied. A family of six living in a considerably more humid part of the world, but short of safe drinking water, such as Garissa, Kenya (normal absolute humidity 17.0 g m^{-3}, Hellström, 1969, Appendix 1) consuming 900 l per day for drinking, kitchen, laundry, and bath would need a 60% efficient AWVP machine capable of 1 m^3 s^{-1} airflow.

AWVP DESIGN AND ENGINEERING

Table 13 summarizes engineering information for AWVP. The wide range of efficiencies, costs, and energy requirements suggests considerable scope for design improvements.

Most designs are adaptable to various scales of water supply from one person to communities of hundreds or thousands. Sizes of AWVP plants will follow from water supply planners decisions on how much distribution infrastructure is desirable.

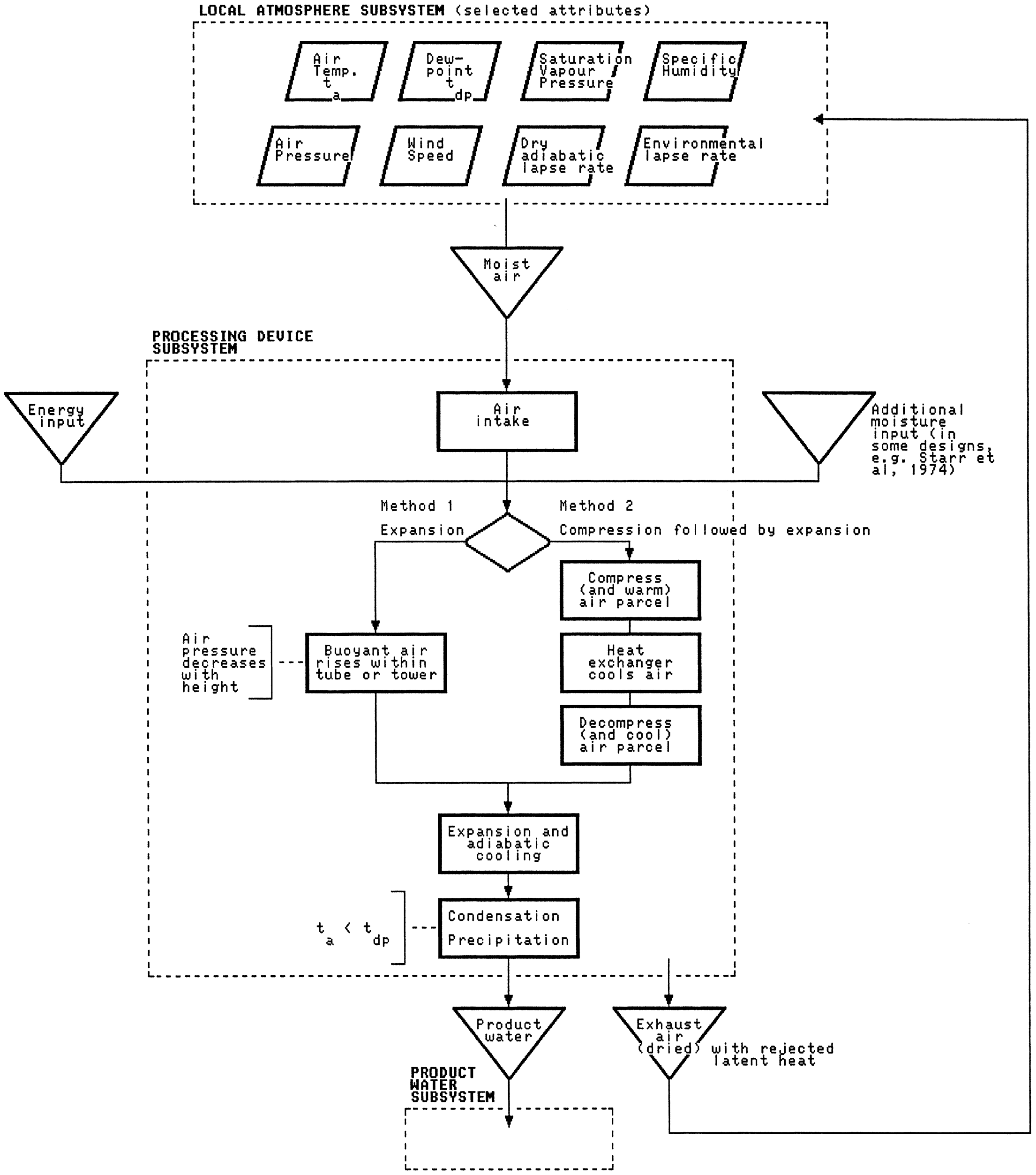

Fig. 5. Design type 3—Convection process for AWVP viewed as an energy and mass cascade.

Table 13. Engineering information for AWVP methods

Engineering information	Type 1—Cooled surface	Type 2—Desiccants	Type 3—Convection
Range of efficiencies			
coefficient of performance, C_P C_P = energy sought/energy cost (Van Wylen and Sonntag, 1985)	2.0–4.5 (Harriman, 1990, p. 3-3, dehumidifiers) 3.2 (ADS, 1999, The Rainmaker®) 324–420 (Paton and Davies, 1996, Seawater Greenhouse)	C_P is not widely used to rate desiccant-type humidifier performance	C_P is not used at present.
efficiency, η, equation (11)	0.19–0.20 (Topp Constr., 1999, Models DRY-42, DRY-100, DRY-200 dehumidifiers) 0.20 (ADS, 1999, The Rainmaker®) 0.20–0.40 (Hellström, 1969, pp. 11–12), dehumidifier used in AWVP trials was more efficient at higher air temperatures	0.35 (Drykor, 1999, Model 601LR, liquid desiccant dehumidifier) 0.68 (DST, 1999, Model R-122, solid desiccant dehumidifier)	0.39 (Meytsar, 1997)
coefficient, C, equation (8)	Efficiency of heat transfer to the air is a function of air velocity and surface size for surfaces cooled by radiation (see text).	not applicable	not applicable
Energy requirements (kWh/m^3 water)	270–500 (refrigerant technology, Table 2); 2.6–15 (deep ocean water coolant, Table 2); 0 for surface cooled by radiation	280 (Drykor 601LR, liquid desiccant); 1305 (DST R-122, solid desiccant)	1800 (Meytsar, 1997)
Temperature difference requirements for condensation	Δt can be relatively small—a few degrees, if the air is close to saturation (dewpoint close to air temperature).	Liquid desiccant systems separate the product water using standard desalination techniques so Δt does not apply.	Δt is relatively large for homogeneous nucleation where no substrate is involved and condensation takes place in the bulk vapour (Beysens, 1995, p. 218). Beysens stated that, "... for example, saturated water vapor at 20°C would condense only around 0°C ..."
$\Delta t = t_a - t_s$ where t_a is air temperature; t_s is temperature of cooled surface	The water vapour phase transition to liquid droplets occurs through a process of heterogeneous nucleation onto a substrate whose surface properties have decreased or eliminated the energy barrier which is related to the liquid–vapour interfacial tension (Beysens, 1995, pp. 216–219). t_s need only be slightly below the dewpoint of the air. It needs to be lower (rather than equal) to compensate for the rate of latent heat released during the phase change as modelled by equation (9).	Solid desiccant systems collect water vapour that is processed into liquid water by a Type 1 cooled surface (see explanation to the left).	Δt will be reduced if there are impurities (analogous to cloud condensation nuclei) in the airflow through the Type 3 processor.
Desiccant requirements	Not applicable	See Table 7 (right-hand column) and Tables 8–12	Not applicable
Capital cost (mainly from Harriman, 1990)	DX[a] least costly. Chilled water mid-range cost. Chilled brine/glycol most costly.	Rotating tray least costly. Multiple vertical bed and desiccant wheel mid-range cost. Solid packed tower and liquid spray most costly.	Unknown
	Small dehumidifiers (25 l fresh water/day) are commonly available starting at about $250.	Manufacturing cost for liquid system is $1270 per m^3/s. Solid system costs about twice as much (NREL, 1999).	
	Industrial air dryers with 1 m^3/s air processing capacity[b] cost tens of $1000s (Van Air, 1997). Radiatively cooled surface cost is material dependent.		
Operating cost (energy and supplies, not including mechanical repairs or preventive maintenance, mainly from Harriman, 1990)	DX[a] and chilled water least costly. Chilled brine/glycol most costly.	Liquid spray and desiccant wheel least costly. Solid packed tower, rotating tray, and multiple vertical bed most costly.	
	Heat pumps: multiply energy requirement above by local cost of energy (e.g. $0.10/kWh). Radiative cooling method has no energy cost.	Multiply energy requirement above by local cost of energy.	Multiply energy requirement above by local cost of energy.

Table 13 (*continued*)

Engineering information	Type 1—Cooled surface	Type 2—Desiccants	Type 3—Convection
Deficiencies in current technology	Minor—widely used commercially/industrially.	Minor—widely used commercially/industrially.	No prototypes other than mine shaft analogue described by Starr *et al.* (1974).
Research needs	Dehumidifiers: Reconfigure for maximizing and capturing condensate and allowing efficient operation in outdoor air. Radiative cooling: experiment with material properties to maximize condensate collection and particularly to promote condensation throughout day, not just at night.	Reconfigure dehumidifiers for maximizing and capturing condensate and allowing efficient operation in outdoor air.	Build and test prototypes.

[a] DX = Direct expansion of a refrigerant gas for cooling of a heat exchanger surface.

[b] Processing 1 m^3 of air per second, with absolute humidity 10 g/m^3, and 40% water recovery efficiency means that 345 l of fresh water is collected every 24 h.

Each building could have its own small AWVP plant, avoiding entirely the need for municipal potable water mains. Or, a neighbourhood could have a large, central AWVP plant from which a distribution infrastructure is built and maintained. Air handling requirements for one person's daily water needs could be accommodated in a small, portable unit while an AWVP plant capable of supplying hundreds of people might be the size of a large industrial building or multi-story office tower.

Dehumidification engineers optimize designs by hybridizing surface cooling and desiccant technologies. (Harriman, 1990). The two methods complement each other. AWVP needs the two working together because, rather than simply exhausting moisture rich air, the device must condense water out of the so-called scavenging (exiting) airstream. Blending economies are likely to be inherent in AWVP designs.

Some references in Table 5 quantified product water output. Cooled surface designs claimed outputs up to 5,860,000 l/d. The solid desiccant system of Groth and Hussmann (1979) would provide up to 100 million l/d. The inventors suggested aquifer recharge as an application. The liquid desiccant processor by Lund (1973) claimed a daily potential output of 1.7 million litres. Convection-based AWVP devices could provide up to 31 million litres daily. These amounts rival the 284,000–45 million litres daily capacity of reverse osmosis desalination plants (van der Leeden *et al.*, 1990, Table 8-60).

Choice of methods is an engineering decision dependent on local climatic conditions and economic factors such as capital, operating, and energy costs. A first consideration of energy costs while blending methods is in Table 14. Air temperature and relative humidity aspects of combining processes are in Table 15. In a hybrid system, the surface cooling subsystem must be capable of coping with the sensible heat load of the desiccant subsystem (Harriman, 1990, pp. 7–15).

AWVP WATER COSTS

Potable water costs ranged from \$0.09/m^3 in Jakarta to retail supermarket bulk drinking water in Canada at \$100/m^3 (Table 16). AWVP water produced with deep seawater coolant is relatively expensive at about \$5.32–\$12.24/m^3. Cost estimates for Chilean fog water, and two AWVP designs are in Table 17 with cost values transferred to Table 16. Profit generating ancillary activities such as agriculture, horticulture, aqua-culture, mariculture, or water sales were ignored. Costs associated with The Rainmaker® were estimated. Advanced Dryer Systems, Inc. (ADS) priced their heat pump based device at US\$1500 and estimated energy costs at

Table 14. Decision table for initial consideration of blending cooling and desiccant technology in an AWVP device according to electricity costs for powering surface cooling compressors/fans and thermal energy costs for reactivating desiccants (from information in Harriman, 1990, p. 3–21)

Energy source/cost	Cheap	Costly
Electric power	cooling	desiccant
Thermal energy	desiccant	cooling

Table 15. Decision table for initial consideration of the most economical AWVP method given certain ambient conditions of air temperature, t_a, and relative humidity, ϕ (from information in Harriman, 1990, pp. 3-20 to 3-21). Low ϕ is taken as being less than 50% and low t_a means close to the freezing point of water. Convection based methods are excluded because sufficient engineering experience is not yet available

Ambient air	Low ϕ	High ϕ
low t_a	desiccant	desiccant
high t_a	cooling or desiccant	cooling

$0.07/kWh (Johnson, 1999a). As higher sales volumes develop, the price is expected to drop to $400–500 (Johnson, 1999b). Using a $500 capital cost in the method of Table 17, a 15 year lifetime, and energy consumption (ADS, 1999) of 480 kWh/(m^3 fresh water) cost of water would be $47/m^3. Although residential dehumidifiers with similar fresh water outputs as The Rainmaker™ can be purchased for $250, they are not intended for potable water production. Johnson pointed out that these do not filter adequately the airflow or provide carbon filtration and water mineralization.

Table 17 highlights difficulties in normalizing water cost data found in the literature. Cost for Chilean fog water was $1.87/m^3 by Cereceda *et al.* (1988) but this was based on a 20 year system lifetime excluding fixed charges. Calculations in Table 17 using a 30 year lifetime including fixed charges were similar to the costing method for desalination plants (United Nations, 1985). Chilean fog water cost $4.46/m^3 by this calculation.

Water for domestic use is a singularly fundamental good with price elasticity of −0.25 (Howe and Linaweaver, 1967 cited in da Cunha *et al.*, 1983 p. 127) which is *inelastic*. A 40% price increase is expected to decrease demand by 10%. Even low income people will pay high prices for clean water. Undue emphasis should not be placed on relative costs when deciding between AWVP and alternatives. Quality, reliability, and convenience affect consumer decisions. Safe and reliable water supply close to, or within, a dwelling promotes mental and physical health plus frees time for occupations other than water-fetching.

AWVP WATER QUALITY

Water extracted from the atmosphere may not be safe to drink. Processing large volumes of air can concentrate pathogens and debris (Michael, 1996). Stored water may suffer contamination. Standard water treatments such as chlorination or disinfection by ultraviolet light or ozone may be required. The condensate can be mineralized to avoid the flat taste of distilled water (Kajiyama, 1974) and for gastric health (Yamamoto *et al.*, 1982). National water quality standards must be met.

Potable water testing for The Rainmaker™ found nitrite nitrogen was 0.094 mg/l, nitrate nitrogen was 0.046 mg/l, lead was < 0.00100 mg/l, and copper,

Table 16. Comparison of ***AWVP costs estimated by author*** (***see also Table 17***) to other options. Costs unadjusted for temporal changes or different cost recovery periods which are noted below, if known, ranging from 10 to 30 years

Option	Cost of water (US$/m^3)	Reference
Municipal, Jakarta, Indonesia	0.09–0.50	Lovei and Whittington (1993) by Gleick (1998)
Municipal, Lima, Peru	0.15	Gleick (1998, p. 46)
Municipal, Goderich, Canada	0.35–0.54 (volume discount)	Public Utilities Comm. … Goderich (1998)
Municipal, urban municipal, USA	0.40–0.80	Gleick (1998, p. 46)
Municipal, Port-au-Prince, Haiti	1.00	Fass (1993) cited by Gleick (1998, p. 46)
Fog-water, Atocongo, Peru (10–15 yr. life)	1.00	Pinche and Ruiz (1996)
Water bag towed 20 km from Piraeus, Greece to island of Aegina (1997)	1.20–1.50	*Financial Times Global Water Report* (1997) cited by Gleick (1998, p. 202)
Desalination: distillation, USA[a]	1.31–2.68 (Higher volumes less cost/unit)	Reed (1982) adapted in UN (1985, p. 31)
Truck tanker, Atocongo, Peru	1.50	Pinche and Ruiz (1996)
Private vendors, Jakarta, Indonesia	1.50	Lovei and W. (1993) by Gleick (1998, p. 46)
Desalination: reverse osmosis, USA[a]	1.54–3.28 (Higher volumes less cost/unit)	Reed (1982) adapted in UN (1985, p. 54)
Tanker truck, Jakarta, Indonesia	1.80	Lovei and W. (1993) by Gleick (1998, p. 46)
Fog water, Chugongo, Chile, (1988), including collectors, pipeline, reservoir, chlorination plant, maintenance and supplies. System lifetime for costing is 20 years.	1.87	Cereceda, Schemenauer, and Suit (1992)
Government supply, Atocongo, Peru	2.00	Pinche and Ruiz (1996)
Proposed combined roof-and-ground catchment system, Botswana (20 yr. lifetime)	2.00–5.00	Gould (1997)
Desalination: distillation, developing countries (at least double USA costs)[a]	2.62–5.36 (Higher volumes less cost/unit)	UN (1985, p. 57)
Vendors, Lima, Peru	3.00	Gleick (1998, p. 46)
Desalination: Reverse osmosis, developing countries (at least double USA costs)[a]	3.08–6.56 (Higher volumes less cost/unit)	UN (1985, p. 57)
Fog water: Chile	***4.46***	***Author's estimate (see Table 17)***
AWVP: Seawater Greenhouse	***5.32***	***Author's estimate (see Table 17)***
Mobile vendors, Port-au-Prince, Haiti	5.50–16.50	Fass (1993) referenced in Gleick (1998, p. 46)
Tanker truck, Chungungo, Chile (1988)	7.25	Cereceda *et al.* (1992)
Entrepreneurs, Rio Vista, Manila, Philippines (60 household community in central Manila)	9	Bolnick *et al.* (1997)
AWVP: Large scale dew collection	***12.24***	***Author's estimate (see Table 17)***
AWVP: The Rainmaker™ (Johnson, 1999)	***47 (15 year lifetime)***	***Author's estimate (method of Table 17)***
Retail supermarket bulk drinking water	100	At *Safeway*, N. Vancouver, Canada (1999)

[a] Desalination costs include capital charges, operation, and maintenance. Capital recovery at 18% interest spans 30 years.

Table 17. Water costing method of United Nations (1985) applied to three innovative water supply examples[a]

Item	Fog Water (Chile); Cereceda *et al.* (1992)				AWVP: Large scale dew collection; Rajvanshi (1981)				AWVP: Seawater Greenhouse; Paton and Davies (1996), Paton (1999)			
	Cost (US$)	Cost (US$/m^3)	Water prod. (m^3/day)	Lifetime (years)	Cost (US$)	Cost (US$/m^3)	Water prod. (m^3/day)	Lifetime (years)	Cost (US$)	Cost (US$/m^3)	Water prod. (m^3/day)	Lifetime (years)
Direct capital costs	115,000	0.53	20	***30***	11,000,000	1.56	643	***30***	3,900,000	0.65	550	***30***
Indirect capital costs:												
Interest during construction		0.00	***)Included in***			0.00	***)Included in***			0.00	***)Included in***	
Working capital		0.00	***)direct capital***			0.00	***)direct capital***			0.00	***)direct capital***	
Contingencies plus A and E fee		0.00	***)costs***			0.00	***)costs***			0.00	***)costs***	
Total capital costs	115,000	0.53			11,000,000	1.56			3,900,000	0.65		
Annual O and M:												
Labour	4800	0.66			***50,000***	0.21	Electricity:		***50,000***	0.25	Electricity:	
Electricity	0	0.00			352,043	1.50	15	kWh/m^3	60,225	0.30	3	kWh/m^3
Replacements	800	0.11			***50,000***	0.21	***$0.10***	per kWh	***50,000***	0.25	***$0.10***	per kWh
Chemicals (stored water treatment)	0	0.00			***40,000***	0.17			***40,000***	0.20		
Other	2400	0.33			***35,000***	0.15			***35,000***	0.17		
Total O and M costs	8000	1.10			527,043	2.25			235,225	1.17		
Fixed charges (18%)	***20,700***	2.84			***1,980,000***	8.44			***702,000***	3.50		
Total annual costs	28,700	3.93			2,507,043	10.68			937,225	4.67		
Cost of water: $/m^3		4.46				12.24				5.32		

[a] General assumptions used in establishing water costs: 1. Direct capital cost includes: site development but not land, infrastructure (common facilities, surface and deep seawater intakes, seawater return, electrical utilities etc.), and plant. 2. Indirect costs include interest during construction, project management, overhead and profits. A = Architecture; E = Engineering; M = Maintenance; O = Operating. ***Author's assumptions shown in bold italic typeface***.

total coliforms, and *E. coli* were undetected, all within United States Environmental Protection Agency standards (ADS, 1999).

PROSPECTS

Although AWVP technology is at an early stage, with the Seawater Greenhouse being the only larger scale design proven in actual operation, development of AWVP has the potential to provide environmentally acceptable alternatives (Wahlgren, 1993) to standard water supplies. Many AWVP designs favour decentralization of water distribution and avoidance of huge capital costs for infrastructure.

AWVPs stage of development is analogous to the internal combustion engine of the late 19th century. Just as evolution of the gasoline engine allowed more personal mobility, dispersion of populations, and better living standards, so evolution of AWVP could let people live comfortably in arid, water scarce regions, easing water supply crises that face millions of people. Fortunately, unlike fossil fuel burning engines, AWVP has few, if any, harmful effects on natural or societal systems. As the water resources community becomes aware of and thinks about AWVP, evolution will accelerate so individuals, family groups, and communities in many regions can become self-sufficient in potable water supply by processing atmospheric water vapour. We should, however, heed Gould's (1997) warning: "Rural Botswana, like much of Africa, is littered with the rusting remains of inappropriate, modern water-supply technologies which have failed to stand the test of a rather short period of time".

Rapid development of appropriate, reliable, and long-lasting AWVP systems is possible by adapting commercial/industrial dehumidification (including compressed air drying) technology. This route was followed by Khanh Dinh, inventor of The Rainmaker™. AWVP proved its value when conventional water supply infrastructure in Taiwan was damaged in the 1999 earthquake. Four Dinh units, each capable of supplying 225 l of fresh water per day, supplied drinking water to a military garrison in Taiwan for a time after the disastrous event (Dinh, 1999).

Harriman's (1990) observation, "Removing excess humidity from the air can have very interesting and profitable consequences", combined with Landsberg's (1972) call to action, "It is about time that serious thought be given to the exploitation, by engineering methods, of that enormous water reservoir in the air", sets the stage for AWVP, an exciting new water supply technology.

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