

# **WATER TREATMENT FOR FOSSIL FUEL POWER GENERATION**

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## **EXECUTIVE SUMMARY**

A 'Technology Status Review of Water Treatment Associated with Fossil Fuel Based Power Generation and Related Processes' has been completed for AEA Technology plc (AEAT), on behalf of the UK Department of Trade and Industry (DTI). The aims of the review were to:-

- Assess objectively the current state of development and application of water treatment technologies relating to fossil fuel power generation world-wide.
- Critically assess the strengths and shortcomings of existing technologies in relation to commercial or near-commercial needs and to provide information on manufacturers, suppliers, developers, consultants and major users.
- Review current activities and capabilities of companies/organisations working in the water treatment technology sector, with particular emphasis on the UK.
- Identify priority areas in which UK RD&D activities could/should be focused to meet future demands.
- Recommend means for enhancing the market opportunities for UK companies and organisations specialising in water treatment technologies.

The main findings of the review are:-

### **Current Status of Technologies**

The use of polymeric organic ion exchange resins for the deionisation of water is now a fully mature and developed technology. Modern ion exchange resins are stable high quality products which have made ion exchange a highly reliable process capable of producing high purity deionised water, even with poor pre-treatment or when subjected to substandard operating practices.

Ion exchange currently remains the preferred and economic choice of treating water containing low total dissolved salts for the purpose of producing deionised makeup water. However, the continuing development of low pressure high flux membranes continues to lower the total dissolved salts barrier at which reverse osmosis systems can be competitive with conventional ion exchange.

Ion exchange technology is currently the only effective option for condensate polishing applications in power plants. There are no available alternative membrane options

Membrane microfiltration is replacing conventional clarification and filtration processes. However, waters with high levels of suspended solids still require to be treated by conventional clarification techniques

Whilst in the last decade, worldwide, there has been a substantial growth in the application of membrane technology within the power industry. In contrast, within the UK, the assimilation of this new technology to produce process water for fossil fuel plants has been slow and conventional established treatment processes such as ion exchange remain the preferred option. This apparent reticence to adopt membrane technology is partly due to the conservative nature of the power industry to new

technology and in part to the reluctance to invest in new plant and technology unless there is an overwhelming economic driver to justify such investment.

The decision to install a straight ion exchange system (IX), reverse osmosis/mixed bed ion exchange (RO/IX) or reverse osmosis/continuous electrodeionisation system (RO/CEDI) will be based principally on economic drivers in terms of capital and operating costs, as well as regional requirements for chemical and waste water disposal. In many cases, familiarity with one or other technology is also a factor in the decision process.

The capital and operating costs of any water treatment technology can only be determined by site specific evaluation due to the wide variability in the characteristics of the water to be treated and the water quality and quantity required by the various power plant processes.

### **World Wide Activities**

The power generation industry will remain a very significant industrial market for water treatment equipment and associated supplies. Growth for water treatment products in the power industry is expected to be typical of overall average growth in industrial water treatment markets.

China represents a huge market for water treatment products and services, but is viewed as a difficult place to do business. Most overseas companies operating successfully within China have done so through maintaining an active local presence. Strong local players are emerging in the Chinese market and are expected to provide increasing competition for power plant water treatment contracts worldwide in the long-term.

There has been significant rearrangement of ownership and increasing consolidation amongst water and waste treatment companies as major industrial corporations have moved to re-position themselves strategically to take advantage of developing opportunities in the water industry. General Electric and Siemens have emerged as major players in the water treatment equipment industry.

Most major equipment and product companies undertake manufacturing in China, India, other Southeast Asian countries and Eastern Europe in order to take advantage of low cost manufacturing facilities, but at some loss of quality in individual plant items.

There are increasing environmental, legislative and cost drivers for power plant worldwide to minimise water consumption and increase recovery. This is expected to have an increasing influence on future water treatment decisions.

### **Market Potential**

Increases in future global electricity demand is expected to be met primarily through large scale fossil fuel based power plant. Whilst coal is projected to continue to retain the largest market share of electricity generation, natural gas fired generation is expected to become increasingly important. The main future markets for new fossil power plant are seen as China and India.

In Western Europe, there is limited need for new capacity in the short term, except in countries where nuclear power is being phased out. However, significant new capacity will be required in a number of countries within the next 10 to 20 years, but uncertainty regarding both the regulatory environment and electricity prices is delaying long term investment in new generating plant.

For countries in Eastern Europe and in the former Soviet Union, there is increasing need for the modernisation of existing plant and retrofits will be more important in the short-term.

## **UK Activities**

In the UK, the introduction of carbon emissions trading this year and the Large Combustion Plant Directive from 2008, combined with the retirement of most nuclear stations, could result in the need to replace almost half of the UK's power stations before 2016. In the short term, additional capacity is likely to be provided by the construction of new gas-fired plant. However, regulatory uncertainty and unfavourable market conditions are holding back investment in new plant by power generators.

The UK CHP market remains unattractive for developers and stronger incentives are required to stimulate a recovery in the market. This has seen greater recent construction of package boilers for electricity or steam production at industrial sites.

The UK has retained few major original equipment manufacturers (OEMs) of water treatment plant for the power industry. There are now two main UK-based companies, Christ Kennicott Water Systems Limited and Elga Process Water (Veolia Water Systems), which have traditionally serviced the power industry and that have retained most UK expertise in this field. These are now owned by overseas parent companies. There are also a number of smaller UK OEMs that operate in the field of industrial water treatment, including the power industry.

There has been some loss of in-house capabilities within UK water treatment plant suppliers for power plant applications in comparison to historical competencies. In recent years, lack of business from the power market has meant that most companies have diversified into alternative market sectors in order to sustain business.

Amongst UK OEMs, Christ Kennicott and Elga Process Water are best placed for new utility and industrial power plant contracts, with well established contacts with main contractors, proven expertise and partnerships and licensing agreements with overseas suppliers. Synergies with affiliated businesses within the parent company group can also provide benefits.

The limited size and experience of the smaller UK OEMs is seen by main plant contractors as a commercial risk for large utility power projects. More success would be expected with small scale industrial power plant. For smaller UK OEMs to be utilised significantly in new power plant build, improved contacts with EPC contractors would need to be established and maintained.

Some international water treatment suppliers also have significant equipment manufacturing or engineering design facilities in the UK for servicing the local market.

There is little UK RD&D activity in the field of industrial water treatment. RD&D is generally carried out overseas by the major water treatment plant suppliers. Most UK OEMs are reliant on technology transfer from equipment suppliers.

# **CONTENTS**

1	Introduction .....	1
2	Water Usage in Fossil Fuel Power Plants .....	2
2.1	Background .....	2
2.2	Potential Water Sources for Use within Fossil Fired Power Plant .....	2
2.3	Characteristics of Surface Water and Groundwater Sources .....	4
2.3.1	Total Dissolved Solids .....	4
2.3.2	Dissolved Organic Matter and Microbiological Activity .....	5
2.3.3	Suspended Solids .....	5
2.3.4	Colloidal Species .....	5
2.4	Potential Effects of Impurities on Power Plant Process Water Treatment Requirements .....	6
2.4.1	Total Dissolved Solids .....	6
2.4.2	Organic Matter .....	6
2.4.3	Suspended Solids .....	7
2.4.4	Colloidal Species .....	7
2.5	Power Plant Water Demand .....	7
2.6	Water Quality Requirements .....	10
2.6.1	Open Recirculating Cooling Water Systems .....	10
2.6.2	Boiler Makeup Water .....	10
2.6.2.1	Power Plant Water/Steam Circuit .....	10
2.6.2.2	Drum Boilers .....	11
2.6.2.3	Once-Through Boilers .....	11
2.6.2.4	Heat recovery Steam Generators .....	11
2.6.2.5	Steam Generator Cycle Chemistry .....	12
2.6.3	Flue Gas Desulphurisation (FGD) Plant .....	13
3	Fundamentals of ion Exchange .....	15
3.1	Commercial Ion Exchangers .....	15
3.1.1	Cation Exchange Resins .....	15
3.1.2	Anion Exchange Resins .....	16
3.2	The Ion Exchange Process .....	16
3.3	Ion Exchange Technology .....	19
3.4	Atmospheric Degasser .....	20
3.4	Mixed Bed ion Exchanger .....	21
4	Overview of Membrane Separation Technology .....	23
4.1	Cross-flow Filtration with Membranes .....	25
4.2	Reverse Osmosis .....	25
4.3	Reverse Osmosis Membrane Materials .....	26
4.3.1	Cellulose Acetate .....	26
4.3.2	Aromatic Polyamide .....	27
4.3.3	Thin Film composites .....	27
4.4	Reverse Osmosis Membrane Modules .....	27
4.4.1	Spiral Wound Membrane Elements .....	27
4.4.2	Hollow Fibre Membrane Elements .....	29
4.4.3	Tubular Configuration .....	30
4.4.4	Plate and Frame Configuration .....	30
4.5	Other Membrane Separation Technologies .....	31
4.5.1	Nanofiltration .....	31

	4.5.2	Ultrafiltration .....	31
	4.5.3	Microfiltration .....	32
	4.5.4	Electrodialysis (ED) and Electrodialysis Reversal (EDR) .....	33
	4.5.5	Continuous Electrodeionisation (CEDI) .....	33
5		Current Status of Thermal Deionisation Technologies .....	35
	5.1	Thermal Desalination Process Options .....	35
	5.2	Comparison of Thermal and Reverse Osmosis Desalination Technologies .....	35
6		Current Status of Water Pretreatment Technologies .....	37
	6.1	Clarification .....	37
	6.2	Filtration .....	39
	6.3	Membrane Microfiltration .....	42
7		Current Status of Ion Exchange Processes for Deionised Water Production .....	45
	7.1	Countercurrent Packed Bed Technology .....	47
	7.2	Stratified or Layered Beds .....	48
	7.3	Uniform Particle Size Resins .....	48
	7.4	Short Cycle Deionisation .....	48
	7.5	Shallow Shell Resin Technology .....	48
	7.6	Ion Exchange Pretreatment Requirements .....	49
	7.7	Operational Problems .....	49
8		Current Status of Condensate Polishing .....	51
	8.1	Application of Condensate Polishing .....	51
	8.2	Condensate Polishing Design .....	51
	8.3	Plant Configuration .....	52
	8.4	Condensate Polishing Resin Regeneration .....	63
	8.4.1	Resin Transfer .....	53
	8.4.2	Resin Separation .....	53
	8.4.3	Resin Regeneration and Remixing .....	54
9		Reverse Osmosis Technologies for Deionised Water Production .....	58
	9.1	Reverse Osmosis System Configuration .....	58
	9.2	Concentrate Recirculation .....	61
	9.3	Concentrate Staging .....	61
	9.4	Flow Distribution .....	62
	9.5	Permeate Staging .....	63
	9.6	Pretreatment Requirements for RO Systems .....	64
	9.6.1	Causes of Scaling and Fouling .....	65
	9.6.2	Pretreatment Technologies .....	65
	9.7	Factors and Operational Issues Affecting RO Membrane Performance .....	65
	9.7.1	Recovery Rate .....	65
	9.7.2	Temperature .....	66
	9.7.3	Pressure .....	66
	9.7.4	Membrane Compaction .....	66
	9.7.5	Concentration Polarisation .....	66
	9.8	Production of Deionised Water Using Reverse Osmosis .....	67
	9.9	High Efficiency Reverse Osmosis .....	68
	9.10	Low Fouling Membranes .....	68
	9.11	The Economics of Ion Exchange versus Reverse Osmosis .....	69
	9.12	Case Studies .....	70



	9.12.1 Case Study 1.....	70
	9.12.2 Case Study 2.....	71
	9.12.3 Case Study 3.....	72
10	Current Status of Water Treatment Technology of Cooling Water Systems.....	76
	10.1 Cooling Water System Operation.....	76
	10.2 Operation at High Concentration Factors.....	78
	10.3 Cooling Water Softening.....	79
	10.4 Pretreatment of Makeup Water.....	79
	10.5 External Treatment of the Recirculating Cooling Water.....	80
	10.6 Suspended Solids Control.....	80
	10.7 Control of Biological Fouling.....	81
	10.8 Alternative Technologies for Cooling Systems.....	82
	10.8.1 Hybrid Cooling Towers.....	82
	10.8.2 Coolers Employing Adiabatic Cooling.....	82
	10.8.3 Dry Cooling Systems.....	82
	10.8.4 Dry Cooling and Plant Economics.....	83
	10.8.5 Case Study : Eskom Experience.....	83
	10.8.6 Turbine Auxiliary Plant Cooling for Dry Cooled Stations.....	84
11	Current Status of Technology for the Treatment of FGD and IGCC Wastewaters.....	85
	11.1 FGD Wastewater.....	85
	11.1.1 Precipitation and pH Adjustment.....	85
	11.1.2 Coagulation and Flocculation.....	85
	11.1.3 Sludge Thickening and Dewatering.....	86
	11.2 IGCC Wastewater.....	88
	11.2.1 IGCC Process Description.....	88
	11.2.2 IGCC Wastewater Streams.....	91
	11.2.3 Wastewater Treatment.....	91
12	Potential for Future Developments.....	93
	12.1 Deionisation by Ion Exchange.....	93
	12.2 Reverse Osmosis Membrane Technology.....	94
	12.3 Other Membrane Technologies.....	94
	12.3.1 Microfiltration Membranes.....	94
	12.3.2 Continuous Electrodeionisation.....	95
	12.3.3 Gas Separation Technology.....	95
	12.4 Emerging and Novel treatment Technologies.....	96
	12.4.1 Ultraviolet Light Technology.....	96
	12.4.2 Magnetic Ion Exchange (MIEX™) Process.....	97
	12.4.3 “On Demand” Condensate Polishing.....	98
13	Water Use at Power Plant.....	99
	13.1 Environmental Legislation.....	99
	13.1.1 European Law.....	99
	13.1.2 UK Statutes.....	101
	13.2 Pressures for Water Reuse.....	101
	13.3 Opportunities for Water Reuse.....	103
	13.3.1 Cooling Water Systems.....	103
	13.3.2 Demineralised Water Treatment Plant.....	103
	13.3.3 Flue Gas Desulphurisation Processes.....	104
	13.3.4 Coal and Ash Handling.....	104

	13.3.5 Equipment Washes .....	104
	13.3.6 Reuse of Industrial Wastewaters.....	104
	13.4 Reduced and Zero Liquid Discharge Systems .....	105
	13.4.1 Introduction .....	105
	13.4.2 Technologies .....	106
	13.5 References .....	112
14	World-Wide Activities .....	113
	14.1 Introduction .....	113
	14.2 Survey Responses.....	113
	14.3 The Global Power Plant Water Treatment Market .....	115
	14.3.1 Market Potential .....	115
	14.3.2 The Chinese Market.....	115
	14.4 Suppliers of Water Treatment Equipment .....	116
	14.4.1 Market Consolidation.....	116
	14.4.2 Profiles of Main Water Treatment Equipment Suppliers.....	116
	14.4.3 Trends in Manufacturing.....	118
	14.4.4 Contract Award by Electronic Auction .....	119
	14.5 Trends in Technologies.....	119
	14.5.1 Ion Exchange .....	119
	14.5.2 Membrane Processes .....	119
	14.6 Water Treatment Outsourcing.....	121
	14.7 Seawater Desalination and Power Plant Co-Location.....	122
	14.7.1 Dual-Purpose Power and Water Plants.....	122
	14.7.2 Co-Location with Membrane Desalination Plants.....	122
	14.7.3 Hybrid (Thermal and Membrane) Cogeneration.....	123
	14.8 Worldwide FGD Activities .....	123
	14.9 References .....	123
15	Power Market Survey.....	125
	15.1 Global Power Generation.....	125
	15.2 UK Market.....	126
	15.2.1 Overview .....	126
	15.2.2 Effects of Environmental Legislation .....	126
	15.2.3 Power Prices .....	127
	15.2.4 Future Construction.....	128
	15.2.5 UK Industrial Market.....	129
	15.3 Western Europe .....	131
	15.4 Eastern Europe and the Former Soviet Union .....	131
	15.5 North America.....	132
	15.6 China .....	132
	15.7 India .....	132
	15.8 Other Asian Countries.....	133
	15.9 Middle East.....	133
	15.10 Australia.....	133
	15.11 Africa.....	133
	15.12 References.....	134
16	UK Activities.....	135
	16.1 UK Power Plant Developments.....	135
	16.1.1 Demineralisation Plant .....	135
	16.1.2 Water Treatment Outsourcing .....	135
	16.1.3 Flue Gas Desulphurisation .....	136

16.2	Prospects of UK Suppliers and Manufacturers in the UK and Global Market.....	136
16.2.1	Overview of UK Suppliers .....	136
16.2.2	EPC Contracts for Power Plant .....	137
16.2.3	Current Perception of UK Suppliers amongst EPC Contractors.....	137
16.2.4	General Prospects for UK Companies .....	138
16.2.5	FGD Wastewater Treatment Plant Projects .....	139
16.2.6	Service Contracts for UK Power Plant.....	139
16.2.7	World Bank Projects.....	139
16.2.8	Long-Term Maintenance of Expertise .....	140
16.3	UK Manufacturers and Suppliers .....	140
16.4	UK Research, Development and Demonstration Activities .....	144
17	Overall Conclusions .....	145
18	Acknowledgements.....	148
	Appendix A EU Water Framework Directive Priority Substances .....	A1
	Appendix B Dangerous Substances Directive Lists.....	B1
	Appendix C Capabilities of Key Players in the Global Water Treatment Market.....	C1
	Ion Exchange Resin Manufacturers .....	C1
	Membrane Manufacturers .....	C2
	Water Treatment Plant Original Equipment Manufacturers.....	C3
	UV and Ozone Disinfection .....	C6
	Appendix D Capabilities of UK Water Treatment Plant Suppliers.....	D1

## **FIGURES**

<b>Figure 2.1</b> : Process Water Flow Diagram for 2000 MW inland Coal Fired Power Plant. (Courtesy of E.ON UK)	9
<b>Figure 2.2</b> : Typical steam/water circuit of a power plant with drum boiler. (Courtesy of E.ON UK)	10
<b>Figure 3.1</b> ; Diagrammatic Representation of Cation Exchange. (Courtesy of E.ON UK)	17
<b>Figure 3.2</b> ; Diagrammatic Representation of Anion Exchange. (Courtesy of E.ON UK)	18
<b>Figure 3.3</b> : Downflow Service –Upflow Regeneration. (Courtesy of E.ON UK)	20
<b>Figure 3.4</b> : Typical Atmospheric Degasser. (Courtesy of E.ON UK)	21
<b>Figure 3.5</b> : Mixed Bed Regeneration. (Courtesy of E.ON UK)	22
<b>Figure 4.1</b> : Filtration Spectrum. (Courtesy of GE)	24
<b>Figure 4.2</b> : Typical Spiral Wound Membrane Element. (Courtesy of Koch Membrane Systems)	28
<b>Figure 4.3</b> : Typical Hollow Fibre Membrane Element. (Courtesy of US Environmental Protection Agency)	29
<b>Figure 4.4</b> ; Continuous Electrodeionisation Process. (Courtesy of EPRI)	34
<b>Figure 6.1</b> : Hopper Bottom Sedimentation Tank. (Courtesy of BEI)	38
<b>Figure 6.2</b> : Sludge Recirculation Tank. (Courtesy of BEI)	38
<b>Figure 6.3</b> ; Process Diagram for Conventional Clarification and Filtration for Treatment of River Water. (Courtesy of E.ON UK)	41
<b>Figure 6.4</b> : Typical Membrane Microfiltration Pressurised System. (Courtesy of Memcor)	43
<b>Figure 6.5</b> : Typical Membrane Microfiltration Immersed System. (Courtesy of Memcor)	44
<b>Figure 7.1</b> : Makeup Water Treatment Plants. (Courtesy of BEI)	46
<b>Figure 7.2</b> : Typical Modern Makeup Water Treatment Plant. (Courtesy of E.ON UK)	47
<b>Figure 8.1</b> : Typical Process Diagram for Condensate Polishing Plant. (Courtesy of E.ON UK)	52
<b>Figure 8.2</b> : Transfer to Separation Vessel. (Courtesy of E.ON UK)	54
<b>Figure 8.3</b> : Transfer from hold tank to Service Vessel. (Courtesy of E.ON UK)	55
<b>Figure 8.4</b> : Resin Clean-up and Separation. (Courtesy of E.ON UK)	55
<b>Figure 8.5</b> : Resin Transfer and Interface Isolation. (Courtesy of E.ON UK)	56
<b>Figure 8.6</b> : Anion and Cation Exchanger Regeneration. (Courtesy of E.ON UK)	56
<b>Figure 8.7</b> : Mixing and Rinsing – Mix and Hold Tank. (Courtesy of E.ON UK)	57
<b>Figure 9.1</b> : Pressure vessel showing membrane elements. (Courtesy of E.ON UK)	59
<b>Figure 9.2</b> : Flow diagram of a two stage RO system. (Courtesy of E.ON UK)	60

<b>Figure 9.3</b> : Flow Diagram of a single stage RO module with concentrate recirculation. (Courtesy of E.ON UK) .....	61
<b>Figure 9.4</b> : Flow diagram of a two stage RO system. (Courtesy of E.ON UK) .....	62
<b>Figure 9.5</b> : Flow diagram of a two stage RO system with permeate throttling. (Courtesy of E.ON UK) .....	62
<b>Figure 9.6</b> : Flow diagram of a two stage RO system with interstage pump. (Courtesy of E.ON UK) .....	63
<b>Figure 9.7</b> : Flow diagram of a partial two pass system. (Courtesy of E.ON UK) .....	64
<b>Figure 9.8</b> : Process Flow Diagram of 1st Stage Reverse Osmosis System. (Courtesy of E.ON UK) .....	74
<b>Figure 9.9</b> : Process Flow Diagram of 2nd Stage Reverse Osmosis and Mixed Bed System. (Courtesy of E.ON UK) .....	75
<b>Figure 10.1</b> : Relationship Between Cooling Circuit Concentration Factor and Make Up Water Flow Rates. (Courtesy of E.ON UK) .....	78
<b>Figure 11.1</b> : Process Flow Diagram of Generic FGD Waste Water Treatment Plant. (Courtesy of E.ON UK) .....	87
<b>Figure 11.2</b> : Diagram of a typical IGCC plant. (Courtesy of Siemens KWU) .....	90
<b>Figure 12.1</b> : Gas Membrane Contactor. (Courtesy of Celgard LLC) .....	95
<b>Figure 13.1</b> : Vapour Compression Brine Concentrator System. (Courtesy of Ionics, Inc.) .....	107
<b>Figure 13.2</b> : Waste Steam Brine Concentrator. (Courtesy of Ionics, Inc.).....	108
<b>Figure 13.3</b> : Forced Circulation Steam-Driven Crystalliser. (Courtesy of Ionics, Inc.).....	109
<b>Figure 13.4</b> : Spray Dryer. (Courtesy of Ionics, Inc.).....	110
<b>Figure 12.5</b> : Guadalupe CCGT Power Station – Site Water Balance. (Courtesy of Ionics, Inc.) .....	111
<b>Figure 15.1</b> : Potential shortfall in UK generating capacity through to 2020. (Courtesy of E.ON UK).....	126
<b>Figure 15.2</b> : Installed CHP capacity in the UK 1996 – 2003. (Courtesy of E.ON UK) .....	130

# **1 INTRODUCTION**

In 2004, AEAT, on behalf of the UK Department of Trade and Industry (DTI), invited proposals for the completion of a 'Technology Status Review of Water Treatment Associated with Fossil Fuel Based Power Generation and Related Processes'. The aims of this review were to:

- Assess objectively the current state of development and application of water treatment technologies relating to fossil fuel power generation world-wide.
- Critically assess the strengths and shortcomings of existing technologies in relation to commercial or near-commercial needs and to provide information on manufacturers, suppliers, developers, consultants and major users.
- Review current activities and capabilities of companies/organisations working in the water treatment technology sector, with particular emphasis on the UK.
- Identify priority areas in which UK RD&D activities could/should be focused to meet future demands.
- Recommend means for enhancing the market opportunities for UK companies and organisations specialising in water treatment technologies.

The review aims to address the range of water treatment technologies applicable to fossil fuel based power generation, including boiler make up water production, cooling water treatment and waste water treatment plant.

The report is broken up into the following sections:

- Water usage in power plant; introduction to power plant water consuming processes and water quality requirements.
- Introduction to water treatment processes; outline of the main water treatment technologies and features.
- Current status of water treatment technologies; review of current commercial applications and relevant operating experience.
- World wide activities; review of companies active in the power plant water treatment market world-wide and their capabilities;
- Market potential; assessment of world-wide trends on the fossil fuel based power generation market;
- UK activities; review of the capabilities of UK companies active in the market.

## **2 WATER USAGE IN FOSSIL FUEL POWER PLANTS**

### **2.1 Background**

Profound changes in the fossil steam and power generation industry have occurred in the last 10 to 15 years. Various technical advancements in unit processes for pre-treatment and dissolved solids removal have resulted in innovative approaches for new water treatment systems and created additional opportunities to upgrade performance and/or reduce the cost of treatment for existing systems. In addition to the technical advances, changes in the fossil steam and power generation industry worldwide have resulted in new relationships between the generation industry and providers of water treatment equipment, consumables and related services. These developments have significantly increased the choices for water treatment that are available to fossil plants at a time when technical resources available to properly evaluate the alternatives are limited in many cases.

This report reviews the available water treatment technologies available for the treatment of the various process water streams used within fossil fired plants. There have been a number of major developments in water treatment technology which are of significant importance to fossil fired plants. The more significant areas of advancement are identified in Table 2.1. Although many of the indicated advancement were available or under development in the last decade, they have not been extensively applied within the worldwide fossil fired steam and power generation market.

<b>Areas of Advancement</b>	
Biofouling Control Options	Membranes for Gas Removal
New Clarification Approaches	Ion Exchange Resins
Ion Exchange Systems	Advanced Filtration Concepts
Continuous Electrodeionisation	Membrane Separation Technology

**Table 2.1 : Water Treatment Technology Advancements**

### **2.2 Potential Water Sources For Use Within Fossil Fired Power Plant**

The process of electricity generation from fossil fuels such as coal, oil and natural gas is water intensive. Between 40 -50% of all water abstracted and used in developed countries is used in the generation of electricity. Thus, a reliable, abundant and predictable source of raw water supply to a fossil fired power plant is a critical factor in the selection of a site location.

Water supplies are required to provide various process waters for the following essential main purposes :

- Boiler makeup water to the water/steam circuit
- NOx control for gas turbines (where required)
- Cooling water for steam turbine condenser
- Auxiliary plant cooling water
- Makeup water to flue gas desulphurisation (FGD) plant (where fitted)
- Ash handling and disposal (coal fired power plant only)

- General domestic use

Raw water for use within a fossil fired power plant may be obtained from a variety of sources, where available in sufficient volumes, although surface waters are most commonly utilised. Freshwater supplies from lakes and rivers are generally considered, although in some instances high salinity waters including seawater are used. Groundwater supplies are typically used in areas where there are insufficient quantities of surface water available of the required quality. Municipal or Towns main water supplies may also be used for certain applications, e.g. water supply to makeup water treatment plant. Municipal supplies generally originate from either surface water or groundwater sources or a combination of both. Such supplies typically have received some degree of pre-treatment which may include clarification, filtration and chlorination.

Freshwater surface supplies, groundwater and municipal supplies have traditionally been the preferred sources of water for inland power plant. Coastal based power plant tend to use estuarine or sea water as the principal source for cooling water with other process water requirements being met typically from municipal supplies.

Worldwide, limitations on the availability of water and increasing environmental pressures to conserve water have stimulated interest in utilising alternative sources of water for use in power plants. Some generating plant, using various water treatment processes, utilise high salinity waters from estuaries or sea to meet all the plant process water requirements. Other plants which are subject to zero liquid discharge restriction recycle and treat internally produced wastewater streams for re-use within the plant. Another potential source of water is the wastewater discharged from municipal sewage treatment plants. There has also been some interest in the water discharges from mine workings. However, in both of these cases, the use of these water supplies is only economically viable if the source of the supplies and the power plant are in close proximity to each other.

The potential sources of water available for use in UK fossil fired power plant are summarised in Table 2.2 along with their current extent of utilisation.



Potential Sources of Water	Extent of Utilisation by UK Fossil Fired Plants
Rivers and Lakes	Widely used by inland based plant for cooling water and other process water requirements.
Estuarine/Sea Water	Use limited to coastal plant. Principally used for cooling.
Groundwater Supplies	Historically, widely used by inland based plant for all water requirements other than cooling. Increasing restrictions on abstraction has lead to a reduction in its use.
Municipal Water Supplies	Widely used as supply for makeup water treatment plant and some cooling applications, particularly in coastal plant. Its use is minimised wherever possible due to its expense.
Internally Generated Wastewaters	Limited and variable usage.
Municipal Sewage Treatment Plant	Only one UK power plant uses this as its primary source of water supply.

**Table 2.2 : Potential Sources of Water for UK Fossil Fired Plant**

### **2.3 Characteristics of Surface Water and Groundwater Sources**

The characteristics of potential surface and underground water supplies for utilisation within a fossil fired power plant vary widely depending on their geographical location and source. The principal impurities present in these waters are total dissolved solids, suspended solids or particulate matter, colloidal species and dissolved organic matter. It is these impurities and their respective levels in the water supply that determine the suitability of the water for use and the necessary treatment requirements to make it acceptable for use in the various processes of a power plant.

#### **2.3.1 Total Dissolved Solids**

Total dissolved solids are a measure of the total soluble ionic constituents of the water. The principal ionic species found in all natural waters are shown in Table 2.3. For comparison, the typical concentrations of each ionic species are also shown for a variety of surface and groundwater sources found in the UK.

Municipal or Towns main water derived from any of these freshwater sources would be expected to have a chemical composition similar to the corresponding typical composition shown in Table 2.3.

It is clearly evident from this comparison of chemical compositions that the total ionic content, i.e. total dissolved solids, of sea water is significantly greater than that of all the freshwater sources available. The high level of dissolved solids and high salinity of sea water has historically precluded its use in many power plant processes, apart from its use in general cooling water systems of the once through design.

Constituent	Freshwater				Sea Water
	Groundwater (Deep Well)	Upland Surface Water	Clean River Water	Industrial River Water	
Calcium	90	12	100	250	1000
Magnesium	120	5	50	100	5500
Sodium	20	8	50	160	24000
Chloride	10	10	50	130	27850
Sulphate	20	5	50	230	2500
Bicarbonate	200	10	100	150	150
Total	460	50	400	1020	61000

1. All concentrations of ionic species are  $\text{mg kg}^{-1}$  as  $\text{CaCO}_3$

**Table 2.3 Typical Chemical Composition of Various Types of Water in UK <sup>1</sup>**

### 2.3.2 Dissolved Organic Matter and Microbiological Activity

Dissolved organic matter normally originates from the natural degradation and decay products of vegetable matter present in the water. Historically, the principal organic species present in natural waters was considered to consist mainly of humic and fulvic acids. However, recent research has identified polysaccharides present in many surface waters. Additionally, pollution arising from industrial waste discharges, storm water discharges and sewage treatment plants are also potential sources of organic matter in surface waters. Similarly, algal blooms and their decay products can cause significant increases in organic levels in surface waters. By their nature, many of these sources of organic matter are variable and seasonal.

Surface waters would also be expected to have some degree of microbiological activity present, e.g. bacteria; the level of which would depend on the source of the water and the degree of pollution present. Groundwater is normally free from microbiological contamination by virtue of the filtration process it undergoes as it percolates through the rock strata... Similarly, due to this filtration effect, groundwater has low organic matter content.

### 2.3.3 Suspended Solids

Suspended solids in surface waters can be in the form of fine silt particles, sand, organic particulate, and other large matter such as vegetation or soil debris. The level of suspended solids in surface waters can vary considerably and fluctuations in levels may be seasonal.

Ground water supplies do not contain any suspended solids due to the filtration effect of the rock strata. However, many groundwater sources contain naturally high levels of dissolved iron and manganese which on exposure to air form an insoluble hydroxide suspensions and deposits. Depending on the level of these species present in the groundwater supply, treatment to remove them may simply require aeration with or without sedimentation, followed by filtration. More difficult waters may require more complicated treatment involving chemicals and clarification.

#### 2.3.4 Colloidal Species

Colloidal species are by definition neither particulate nor in solution. They are too small to be removed by conventional filtration. The most common colloidal species encountered in waters is colloidal silica. Colloidal silica is rarely present in groundwater.

### **2.4 Potential Effects of Impurities on Power Plant Process Water Treatment Requirements**

#### 2.4.1 Total Dissolved Solids

For many power plant process water requirements using freshwater supplies, it is unnecessary to remove or reduce the total dissolved solids prior to use. However, in some particular processes where the process water is subject to substantial evaporation losses, this results in a concentration of the dissolved solids in the process water, e.g. in a recirculating cooling tower system. As high concentrations of dissolved solids in the cooling water may cause scale formation by precipitation of calcium salts, it may be necessary to mitigate potential scaling problems by controlling the concentration of these salts through system purging and/or use of antiscalant chemical additives.

In the production of makeup water for modern high pressure boiler plant only traces of ionic impurities in the makeup water are permitted. It is therefore necessary to remove all ionic constituents from the raw water to achieve the high purity that is required. Historically within the UK, ion exchange processes were the most common treatment technology used to provide high purity makeup water to high pressure boilers. However, in the past few years, due to proven reliability and performance, membrane separation technology has become more acceptable and several membrane based makeup water treatment systems have been installed in existing UK fossil fired power plant as part of ongoing plant refurbishment programmes.

Worldwide, proven reliable membrane separation technology, i.e. desalination by reverse osmosis, can enable sea water to be used as the primary water source for all power plant water requirements. However, this particular application has still to be adopted by coastal power plant in the UK.

The respective concentrations of each of the ionic constituents present in a raw water supply to a makeup water treatment plant are critical factors in the design and performance of any makeup water treatment plant whether it is based on ion exchange, membrane technology or a combination of both. Thus, the chemical composition ultimately dictates the water treatment requirements and the overall design, configuration and performance of the makeup water treatment plant.

#### 2.4.2 Organic Matter

The presence of dissolved organic matter in boiler makeup water supplies can pose serious potential risks to the integrity of steam turbines. Within the steam/water circuit of boiler plant these dissolved organic species undergo degradation to form simple organic acids species such as acetic and formic acids... These acidic species in steam tend to concentrate in the first condensate droplets/films formed within the turbine, depressing

the pH at the dry/wet steam phase transition zone in the low pressure cylinder. Organic acids in steam have been known to cause general corrosion in turbine cylinders. Additionally, acetate and formate species have been linked to a specific role in stress corrosion cracking.

Thus, it is imperative that the levels of dissolved organic matter in boiler makeup are maintained as low as reasonably possible. Dissolved organic species are only partially removed by conventional coagulation and clarification. Anion exchange resins have the capability to remove dissolved organics but their efficacy is dependent on the size, polarity and concentration of the organic molecules present in the water. Additionally, anion exchange resins are susceptible to fouling by dissolved organic species which has a detrimental impact on their performance. The only treatment technology currently available that will consistently reduce organic levels in makeup water supplies to acceptable levels is reverse osmosis membrane technology.

The larger suspended organic material present in surface waters can often be removed by coarse screening or conventional filtration. Finer particulate would require a combination of clarification and filtration.

#### 2.4.3 Suspended Solids

The type of treatment required to remove or reduce suspended solids will depend on the level of suspended solids present in the water supply and the particular process water requirements. Within the UK, the quality of river water supplies, in terms of suspended solids, is normally suitable for direct use in cooling tower systems and flue gas desulphurisation plant. If suspended solids in the river water supply are high and likely to lead to silting and fouling problems in cooling towers and cooling water circuits, clarification and/or filtration of the water may be necessary before use.

River water used to supply makeup water treatment plants will generally require some form of clarification and/or filtration prior to its treatment by ion exchange or membrane technology.

Municipal water supplies contain negligible suspended solids. However, it is normally good practice to pretreat these water supplies by simple filtration to remove any pipework corrosion debris present, prior to being fed to ion exchange or membrane based makeup plant.

#### 2.4.4 Colloidal Species

Colloidal silica is non-ionic and cannot be removed by ion exchange technology. Partial removal of colloids can be achieved by flocculation/clarification. Complete removal can only be achieved by use of appropriate membrane separation technology.

### 2.5 Power Plant Water Demand

Traditionally, the largest single demand for water has been associated with the cooling water system for the steam turbine condenser. The function of this cooling water system is to cool and condense the steam exhausting from the turbine to enable its return to the boiler water/steam circuit as feedwater. In condensing the steam, the

temperature of the cooling water typically increase by 5 – 10°C as it passes through the condenser absorbing the latent heat of the condensed steam.

There are principally two types of wet cooling system employed in fossil fired power plant; once through/direct cooling system and open recirculating cooling system. In the once through cooling system, the cooling water is abstracted from the water source, pumped through the condenser and then the warm water is discharged immediately back to the source of abstraction. Once through cooling systems are mainly employed at coastal power plant where large volumes of water are normally available for cooling. At power plants located inland, rivers are unable to provide the large volumes of water required by once through cooling systems. Hence, inland plants typically utilise the open recirculating cooling system with evaporative cooling towers to reduce their cooling water requirements. As a comparison, the cooling water abstraction requirement for a typical 2000MW coal-fired station with a once through system is approximately 6.5 million m<sup>3</sup>/day. In contrast, a similar power plant with a recirculating cooling system would only require 0.2 million m<sup>3</sup>/day.

The second largest single consumer of water is the makeup water treatment plant. The function of this plant is to produce water for use in the boilers of fossil fuel power plants. The makeup water replaces water and steam lost from the plant water/steam circuit as a result of leaks, drainage, boiler blowdown and any steam exported to third parties. The makeup water for modern fossil fuel boilers has to be high purity deionised water with virtually complete removal of impurities. For some combined cycle power plant, there may be an additional requirement for deionised water for injection into the gas turbines to control NO<sub>x</sub> emissions.

The quantity of boiler makeup water required generally ranges from 1–3% of the maximum continuous rated steam flow of the plant. However, makeup volumes can be as high as 100% for some combined cycle or CHP plants which export steam to other industrial processes. Similarly, the mode of operation of the power plant will also affect makeup water requirements, e.g. two-shift operation requires higher levels of makeup water. For a four unit 2000MW coal-fired power plant, maximum makeup requirements are typically around 4600 m<sup>3</sup>/day. To produce this amount of makeup water would require a raw water supply in the region of 5000 –6000 m<sup>3</sup>/day, depending on the treatment process used to produce deionised water and the quality of the raw water supply.

As noted earlier, other areas of power plant operation also have water requirements. The principal areas of water use are shown in the water flow diagram presented for a 2000MW inland coal fired power plant fitted with flue gas desulphurisation (Figure 2.1).

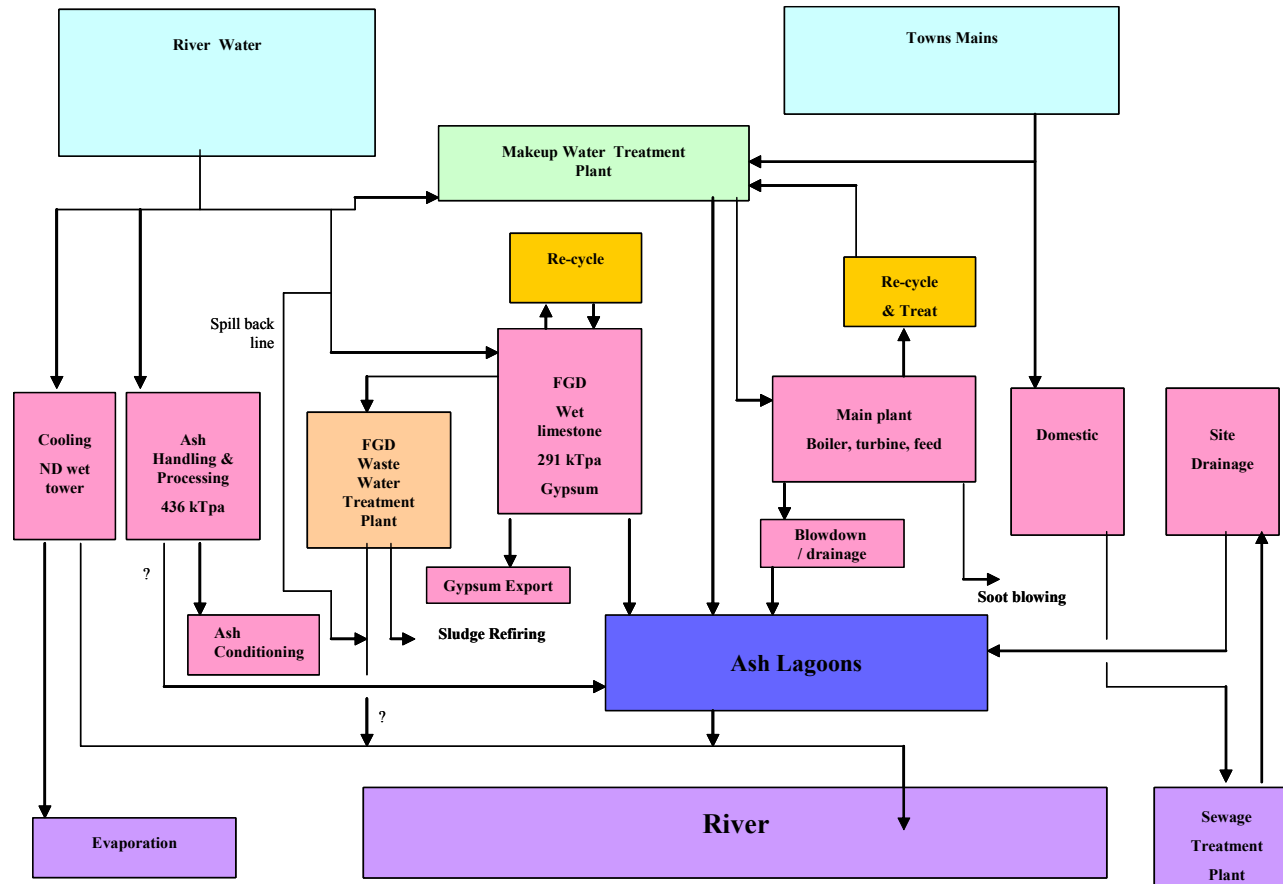


Figure 2.1 : Process Water Flow Diagram for 2000MW inland Coal Fired Power Plant (Courtesy of E.ON UK)

## 2.6 Water Quality Requirements

### 2.6.1 Open Recirculating Cooling Water Systems

There are no specific industry standards for quality of water to be used within open recirculating systems. Generally, cooling tower manufacturers would take cognisance of the quality of the makeup water available, including suspended solids, in the design of the cooling system. They would also expect to make recommendations on any treatment requirements to mitigate any potential scaling, fouling, silting and corrosion issues whilst operating at the design concentration factors.

The majority of open recirculating cooling water systems in the UK use either untreated river or estuarine water as the principal source of makeup water. In other parts of the world, pre-treatment of makeup water and or treatment of the recirculating cooling water is often undertaken to minimise scaling and fouling problems.

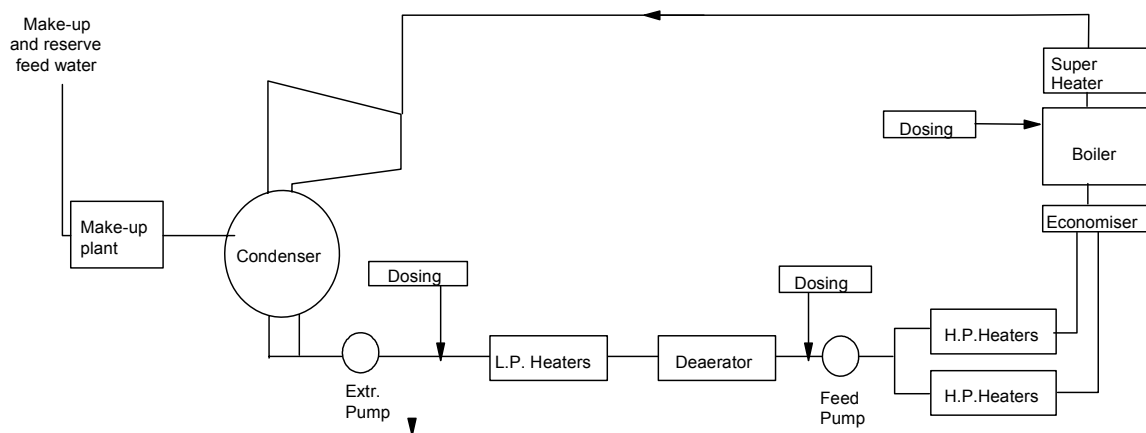
### 2.6.2 Boiler Makeup Water

The primary application of modern water treatment technology is to maintain the integrity and performance of the steam generator components. Experience has shown that integration of water technology treatments with steam generator design can be very important by reducing operational problems and component failures.

To restrict the corrosion of feed system component materials and minimise the transport of corrosion products and corrosive contaminants to the steam generator, it is essential that the quality of the feedwater is maintained of sufficient purity. To attain this goal, conditioning of the feedwater is achieved through a variety of chemical treatments. Depending on the steam generator design and feedwater quality requirements, further treatment of the feedwater utilising condensate polishing systems may be necessary.

#### 2.6.2.1 Power Plant Water/Steam Circuit

A basic process diagram of a steam/water cycle system for a drum boiler system is shown in Figure 2.2.



**Figure 2.2 : Typical steam/water circuit of a power plant with drum boiler  
(Courtesy of E.ON UK)**

### 2.6.2.2 Drum Boilers

In a drum boiler, water flows from the drum via downcomers and feeder pipes to the bottom of the furnace where it feeds the evaporator tubes forming the furnace envelope. Within the furnace, tubes are heated and the water is gradually changed to a water/steam mixture of increasing dryness along its length. This mixture is returned to the drum where dry steam is separated from the mixture. Since the water/steam in the furnace tubes is of lower density than the water in the downcomers, a static head difference is generated and this results in a downward flow in the downcomers and an upward flow in the furnace tubes. With natural circulation boilers, the flow around the boiler is generated solely by this density difference. With assisted circulation boilers, the flow receives additional assistance from pumps usually located at the bottom of the downcomers.

It is evident that drum boilers are dependent on the differences in density between steam and water and, as pressure increases, these densities converge until at and above the critical pressure they are equal. Drum boilers are therefore restricted in pressure to somewhat below critical pressure, with the limit of economic designs being somewhere around 183bar.

In a drum type boiler any impurities entering with the feedwater, concentrate in the boiler water and will normally be either carried over with the steam or removed via the boiler blowdown. Thus, these boilers are generally tolerant of low levels of non-volatile dosing chemicals and impurities.

### 2.6.2.3 Once-through Boilers

Once through boilers can operate below or above the critical pressure as flow in the boiler is imposed by the feed pump. The essential difference between once-through boilers and drum boilers is that all the water entering the boiler tubes is evaporated to dry steam in a series of parallel single pass boiler tubes. If the boiler pressure is above the critical point of steam, i.e. of the supercritical design, there is no phase change across the boiler tubes. By their very design, all adventitious impurities or feedwater conditioning chemicals must either deposit in the boiler tubes or pass through to the turbine with the steam. Thus, the nature and extent of problems to which once-through boilers are susceptible are in many respects quite different from those of drum-type boilers.

In once-through boilers any impurities present in the feedwater is deposited on the inner walls of the tubes. Boilers of this design are therefore intolerant of non-volatile dosing chemicals and impurities.

### 2.6.2.4 Heat Recovery Steam Generators

Heat recovery steam generators (HRSG's) absorb their heat from hot gas that has been exhausted from a combustor to produce steam. Usually the source of the hot gas is the exhaust from a gas turbine but it could also be a fluidised bed combustor or an internal combustion engine. The majority of HRSG's are drum boilers and cover a wide range of designs, applications and operating pressures (10 -130bar). Typically, their main



applications are in combined cycle gas turbine power plant (CCPP) and combined heat and power (CHP) or cogeneration plant.

In earlier CCPP, the HRSG was of the single drum design. However, most HRSG now have multiple pressure circuits with separate low, intermediate and high pressure boilers. A combination of once-through and drum steam generators may also be used.

CHP plant is typically either single pressure or dual pressure design. In CHP plant, a proportion of the steam generated is exported to third party industrial processes. The steam is then normally returned to the power plant as condensate. The amount of condensate returned varies for each particular plant and can range from 100% to zero return of the original steam exported. If there is a potential for the condensate to be contaminated by the industrial process in which it is being used, it is normal practice to treat the returned condensate by a variety of techniques before its re-use in the steam/water cycle.

#### 2.6.2.5 Steam Generator Cycle Chemistry

The major objectives of feed and boiler water chemical treatment are to minimise deposition and corrosion of the feed system components and boiler evaporator surfaces and to ensure that the steam generated is of the appropriate quality. The optimum boiler water condition is mildly alkaline at operating temperatures and pressures. Under such conditions the boiler steel is passive and the potential for corrosion is minimised. Any deviation from such conditions carries a risk of damage to the boiler. Boiler water is maintained alkaline through the dosing of alkalisising conditioning chemicals to the boiler water circuit. Solids alkalis, such as sodium hydroxide and sodium phosphate, or volatile ammonia are commonly used to achieve the correct alkaline conditions in both drum type boilers. Volatile amines may also be used as alkalisising agents, particularly in CHP plant.

The chemical control of once-through boilers has some different requirements. As these boilers are not tolerant of non-volatile impurities, solid alkalis cannot be used and chemical conditioning is based wholly on volatile alkaline chemicals such as ammonia. Another major difference between drum and once through boilers is the need for very high purity feedwater in the latter, which generally requires the use of full flow condensate polishing to ensure feedwater quality.

Typical qualities for deionised water are shown in Table 2.4.

PARAMETER	MAXIMUM IMPURITY CONCENTRATION	
	Makeup water to water/steam cycle	Gas turbine injection for NO <sub>x</sub> control
Specific Conductivity (µS/cm)	< 0.20	< 1.0
Sodium + Potassium (µg/kg Na + K)	< 10	< 100
Silica (µg/kg SiO <sub>2</sub> )	< 20	< 200
Iron (µg/kg Fe)	≤ 20	≤ 5
Copper (µg/kg Cu)	<3	≤0.01
Total Oxidisable Carbon (µg/kg C)	< 200	

**Table 2.4 : Typical Deionised Water Quality Requirements**

### 2.6.3 Flue Gas Desulphurisation (FGD) Plant

The term Flue Gas Desulphurisation (FGD) covers a range of technologies which can be applied to treat the flue gas from coal-fired and oil-fired power stations in order to reduce emissions of sulphur dioxide. The FGD equipment can either be installed during the original build program of a new power plant or as a retrofit to an existing power plant. As well as reducing SO<sub>2</sub> emissions, FGD technologies can also contribute to a reduction in hydrogen chloride, sulphur trioxide and particulate emissions. The FGD technologies can be divided into three main categories, namely, wet, dry and semi-dry processes.

Wet FGD systems utilise an aqueous alkaline solution, which is brought into contact with the flue gas in a spray tower, typically situated at the back end of the power station immediately before the stack. There are a number of wet FGD processes, the most widely applied of these is the limestone-gypsum process, which uses limestone slurry as the aqueous reagent and produces a gypsum product stream, which is typically of saleable plasterboard quality. There are a number of variations on the limestone-gypsum process, such as the lime-gypsum process and the limestone-throwaway processes, the first of which uses a more reactive reagent and the second produces a by-product which requires disposal. Another wet FGD process, similar in many respects to the limestone gypsum process, is the ammonia scrubbing process which uses aqueous ammonia as the reagent and produces ammonium sulphate, which is a saleable fertiliser. Both of these wet FGD processes and their derivatives will require a process water stream in order to produce the aqueous reagent, to make-up water evaporated and lost into the flue gas stream in the absorber tower, to replace liquid lost with the product stream and, where required, to balance the purge stream applied to control the level of impurities within the system. In many circumstances a purge stream is required from a limestone gypsum FGD plant in order to control the chloride level in the recirculating slurry and to reduce the level of trace element impurities in order to maintain the gypsum quality. The purge stream is treated in a waste water treatment plant to precipitate trace elements and remove fine solid matter prior to discharge from the site.

The seawater FGD process is a wet FGD process and utilises seawater as its main process water stream. The seawater FGD process varies significantly from the limestone-gypsum process in that it uses the natural alkalinity of the seawater cooling water (CW) discharge stream from coastal power plants as the reagent stream responsible for removing SO<sub>2</sub>. The final 'product' is seawater, which having passed through the FGD absorber and aeration stages, is typically discharged with slightly higher sulphate content and a slightly reduced pH value than with which it entered the plant.

The semi-dry FGD processes, such as the circulating fluidised bed (CFB) process, the spray dry process and the duct spray dry process, utilise hydrated or 'slaked' lime (calcium hydroxide) which is prepared by adding a stoichiometric amount of water to a lime (calcium oxide) feed stream. Additionally process water is added to humidify and cool the flue gas, this aids SO<sub>2</sub> removal and is either achieved by adding additional process water to the reagent to produce slurry or through direct injection of additional process water into the flue gas. No waste water purge stream is produced as the process by-product is all collected within the ash collection system, or in a dedicated FGD by-product collection system, as a particulate stream.

As their classification implies, the dry FGD processes, such as the sodium bicarbonate injection process, do not require process water and do not produce a waste water discharge stream. An exception to this is the furnace sorbent injection process which requires minimal process water to hydrate a lime feed to produce the slaked lime reagent, which is then injected directly into the furnace as a dry solid powder.

Process water is consumed in a number of ways throughout the Wet FGD process. The flue gas becomes saturated during contact with the limestone slurry in the absorber and hence evaporation is the major pathway through which process water is consumed. Two water molecules are also consumed during the crystallisation of each molecule of SO<sub>2</sub> as calcium sulphate dihydrate (gypsum). The final gypsum product is dried by either vacuum belt filter or centrifuge and the recovered process water is recycled back into the process, however, the gypsum product stream leaving the FGD plant typically contains around 8-10% residual moisture and this represents a further loss of process water from the system. A wastewater purge stream is usually extracted in the limestone gypsum FGD process in order to control the chloride concentration in the slurry to a level which is acceptable for the materials of construction and avoids hindering the limestone dissolution process. The waste water purge stream also removes trace element impurities from the process liquor in order to maintain the gypsum quality. The chloride level of the recirculating slurry is derived from chlorine in the fuel which exists as hydrogen chloride in the flue gas and is then removed alongside the SO<sub>2</sub> in the FGD spray absorber and significantly augments any background chloride level associated with the process water make-up stream. Trace element impurities enter the system as fly ash passing through the particulate collection device and are also a component of the limestone reagent. The make-up process water stream required to replace moisture lost within a limestone gypsum FGD plant through evaporation, crystallisation, gypsum moisture and the waste water purge stream is typically taken from the same fresh water source as the water used for the power plant cooling water supply and can be introduced to the system primarily as demister wash water at the top of the absorber, or for washing of the gypsum product or during limestone slurry preparation. A number of further process activities will contribute to a small additional process water requirement;

these include operations such as humidification of the oxidation air supplied to the process liquor in the absorber and intermittent washing of the regenerative gas-gas heat exchanger elements.

The FGD process water is normally untreated river water, generally abstracted via the power plant main cooling water system. If adequate supplies from this source are not available or if the available water is saline water within the cooling water system, alternative process water sources such as municipal towns water or a desalination plant may have to be considered.

The actual process water consumption of an individual limestone gypsum FGD plant will be a site specific and operating condition specific issue. The degree of evaporation will be dictated by the temperature and humidity of the flue gas entering the absorber. The water of crystallisation and the gypsum moisture will be proportional to the mass flow of gypsum product and hence the fuel sulphur content and the required FGD removal efficiency. The waste water purge stream will depend upon the chloride content of the fuel, although in some low chlorine fuel circumstances the waste water treatment may be required to control trace element levels or omitted altogether if the moisture entrained within the gypsum product stream provides a sufficient degree of purge. An indicative throughput of process water for a typical FGD plant treating flue gas from a generic 2000MW UK power plant would be of the order of around 80kg/s, although as described above the exact flow rate of an individual plant will ultimately be determined by the composition and properties of the flue gas entering the FGD plant at that time. In this illustration a waste water treatment stream of the order of around 20kg/s would be passed to the WWTP.

### **3 FUNDAMENTALS OF ION EXCHANGE**

The ion exchange process is based essentially on a reversible exchange of ions between an external aqueous liquid phase and an ionic solid phase. The solid phase consists of a crosslinked polymeric matrix that is insoluble but permeable to the external aqueous phase. This polymeric matrix contains fixed charge groups and mobile counter ions of opposite charge. These counter ions can be exchanged for other ions in the external aqueous phase.

Ion exchange is used in water treatment processes to replace undesirable ions present in water with more desirable ions. It is achieved by passing water through a bed of insoluble synthetic polymeric beads of ion exchange resins.

#### **3.1 Commercial Ion Exchangers**

Traditionally, ion exchangers have been produced as beads of resins with a size grading between 0.3 and 1.2mm. For specialist applications resins were produced with a narrower bead size distribution. More recently standard grade ion exchangers have been produced with much narrower bead size distributions, e.g. 0.4 - 0.8mm. These have advantages in more effective regeneration as well as faster rinse out of regenerants and a lower pressure drop in service.

Ion exchange resins can be obtained either as gel or macroporous type. Gel ion exchange resins are composed of a crosslinked polymer matrix which results in the formation of a homogeneous continuous phase throughout the bead. Gel resins exhibit microporosity with pore volumes typically up to 10 to 15 Ångstroms. Macroporous resins are produced from a styrene-divinylbenzene copolymer to which has been added a non-polymerisable diluent that volatilizes leaving discrete macro pores with diameters of several hundred Ångstroms throughout the bead. These pores are considerably larger than those found in gel resins and, as such, allow the accessibility of large molecules. Macroporous resins are frequently used where rigorous conditions are encountered since the increased crosslinkage permits resistance to resin degradation caused by such factors as osmotic shock, attrition and oxidation.

There are essentially two basic types of ion exchange resins; cation and anion exchange resins.

##### **3.1.1 Cation Exchange Resins**

There are two categories of cation exchange resin. The most common is the strong acid cation exchanger which is effective over a wide pH range. Strong acid cation exchange resins typically comprise of styrene divinylbenzene copolymers with sulphonic acid functional groups which act as primary cation exchange sites. These resins can neutralise strong bases and convert neutral salts into their corresponding acids.

The second type is the weak acid cation exchange resin which generally consists of a crosslinked acrylic polymer with a carboxylic acid functional group. This particular type of cation resin is only effective in alkaline conditions. Weak acid cation resin is only able to neutralise strong bases.

### 3.1.2 Anion Exchange Resins

Anion exchange resins also have strong base and weak base types. Typical strong base anion exchange resins comprise of styrene or acrylic divinylbenzene copolymers with quaternary ammonium functional groups which act as anion exchange sites. Like the strong acid cation resins, the strong base anion resins can operate over a wide pH range. These resins can neutralise strong acids and convert neutral salts into their corresponding bases

The weak base anion exchange resins are of similar polymeric matrix but contain weaker amine functional groups. The weak base exchangers are only effective in acidic solutions and exchange only ions such as chloride, nitrate and sulphate, but not silica or bicarbonate.

Weak base exchangers are more efficiently regenerated than strong base types, but their application is limited to certain types of raw water that has high concentrations of chloride, nitrate and sulphate. Strong base anion exchangers will exchange all anions including silica and bicarbonate.

All anion exchangers are much more sensitive to temperature than cation exchangers. The active anion exchange groups, particularly of the strongly base types, undergo a slow chemical degradation as the operating temperature increases. Whilst the anion resin types based on an acrylic polymer are very good for organic matter removal, they have an upper temperature limit of 30°C for continuous operation, whereas the polystyrene polymer types have a higher limit of 40-50°C.

### 3.2 The Ion Exchange Process

When a solute is dissolved in water its components are present in solution as ions. The simplest case is sodium chloride which, in solution, consists of sodium and chloride ions. Sodium ions have a positive charge and all positively charged ions are known as cations. Chloride ions have a negative charge and all negatively charged ions are called anions. Some cations have a single positive charge, some have two or even three units of charge. Typical examples of common cations are given below:

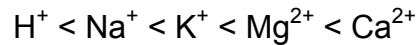
Sodium	Na <sup>+</sup>
Potassium	K <sup>+</sup>
Calcium	Ca <sup>2+</sup>
Magnesium	Mg <sup>2+</sup>

Typical examples of common anions are:

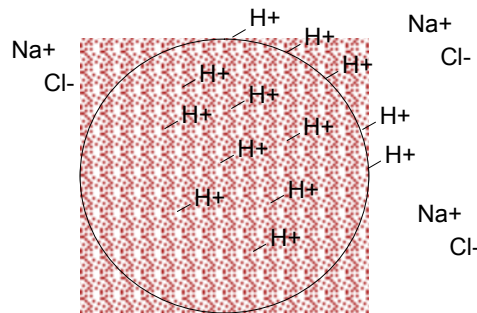
Chloride	Cl <sup>-</sup>
Nitrate	NO <sub>3</sub> <sup>-</sup>
Bicarbonate	HCO <sub>3</sub> <sup>-</sup>
Sulphate	SO <sub>4</sub> <sup>2-</sup>
Carbonate	CO <sub>3</sub> <sup>2-</sup>
Phosphate	PO <sub>4</sub> <sup>3-</sup>
Silicate	HSiO <sub>3</sub> <sup>-</sup>

Ions with a single charge are known as monovalent and with a double charge are divalent. It is a principle of solution chemistry that the overall charge of the solution is neutral, i.e. the positive charges of the cations exactly balance the negative charges of the anions.

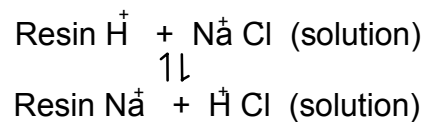
Cation exchange resins have the property that they prefer to associate with cations of higher valence relative to cations of lower valence and show a selectivity sequence typically:



Therefore, if the cation resin is loaded with mobile hydrogen ions initially and is placed in a solution containing sodium chloride a significant number of the hydrogen ions associated with the polymer will be exchanged for sodium ions, as shown in Figure 3.1.



▪ Equilibrium



**Figure 3.1 ; Diagrammatic Representation of Cation Exchange  
(Courtesy of E.ON UK)**

This reaction is written as:

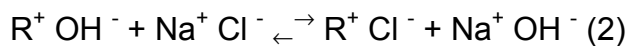


The  $R^-$  refers to the fixed polymer phase of the cation exchange resin. The symbol between the two halves of the equation [ $\rightleftharpoons$ ] shows that the reaction is reversible. If water containing sodium chloride, or other salts is passed through a bed of cation exchange resin in the hydrogen ion form the sodium ions will be removed and replaced in solution by hydrogen ions. This will cause the water coming out of the bed of cation exchanger to be more acidic than the water going in. Cation exchange will continue until the exchanger is saturated with sodium ions and no more are removed from the incoming solution. Because ion exchange is a reversible process the cation exchanger can be “regenerated” by passing through it a concentrated acid solution, typically hydrochloric or sulphuric acid, and rinsing away the excess acid. The cation exchanger is then ready to exchange further cations. The requirement for maintenance of charge neutrality is maintained at all times.

Anion exchange occurs by a basically similar process (Figure 3.2). In this case the anion resin is chemically modified to have fixed positive charges and mobile negatively charged anions. Commercially available anion exchangers have a selectivity sequence that favours all common anions relative to hydroxide ion:-

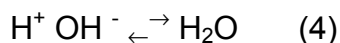
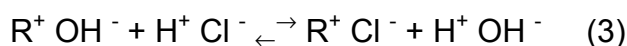


Using the sodium chloride example again but this time passing the solution through a bed of hydroxide form anion exchange resin, the anion exchange reaction is:



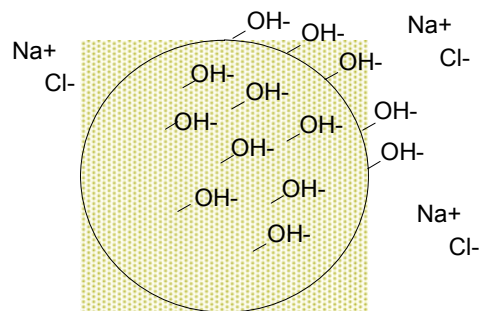
Thus, when the bed of hydroxide form anion exchange resin is exhausted to chloride ion it can be regenerated by contacting it with a concentrated alkali solution, typically sodium hydroxide. [ $R^+$  represents the fixed phase anion exchanger.]

If the product water from hydrogen forms cation exchanger [reaction 1] is then passed through a bed of hydroxide form anion exchange resin the net result is pure water, [3] and [4].

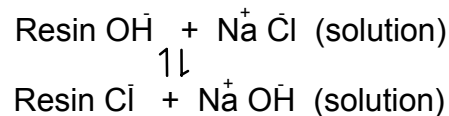


Therefore, with the combination of cation and anion exchange resins all ions from a raw water supply can be removed to produce purified water. However, the fact that the ion exchange reactions are reversible equilibria means that it is very difficult to force the exchange reaction to completion. Therefore, in commercial ion exchange plants ion exchangers are rarely fully exhausted or fully regenerated. The effect is that a simple two bed ion exchange process, cation exchange followed by anion exchange, will remove the majority of impurities in the raw water but will not produce 100% pure water.





▪ Equilibrium



**Figure 3.2 ; Diagrammatic Representation of Anion Exchange  
(Courtesy of E.ON UK)**

### 3.3 Ion Exchange Technology

Ion exchange generally takes place with a fixed bed of resin beads through which the water is passed. It is a batch process in which the water is passed through a bed of exchange resins until a pre-determined end point is reached. This may be based on a fixed throughput or may be when a measured control parameter is exceeded. For example, the outlet conductivity or another chemical parameter measured by on-line analysers may exceed a pre-set value indicating that an unacceptable concentration of ions from the influent water are passing through into the treated water.

Ion exchange generally takes place in a vertical cylindrical vessel to which various associated pipes and valves are attached to control the flows of influent water, regenerant chemicals and rinse water. Inside the vessels are pipework with distribution and collection systems for the various water and regenerant flows. The effectiveness of

these headers and collectors has a significant influence on the overall performance of a bed of ion exchange resin. Header design can vary from a simple splash plate, through to headers with laterals that distribute water through holes or slots to a full diameter plate with nozzles or perforations in it. All slots and perforations must be designed to retain the resins within the vessel. The vessels are generally manufactured from mild steel and to protect them from the acidic or alkaline conditions during regeneration conditions they are lined with a rubber or other compatible protective coating.

For the majority of ion exchange plants the normal flow of water being treated is downward through the bed, although there are systems where the direction is up-flow and the resin is held against a nozzle plate at the top of the vessel by the flow of water. This type of packed bed plant is more susceptible to fouling by particulate matter in the influent water.

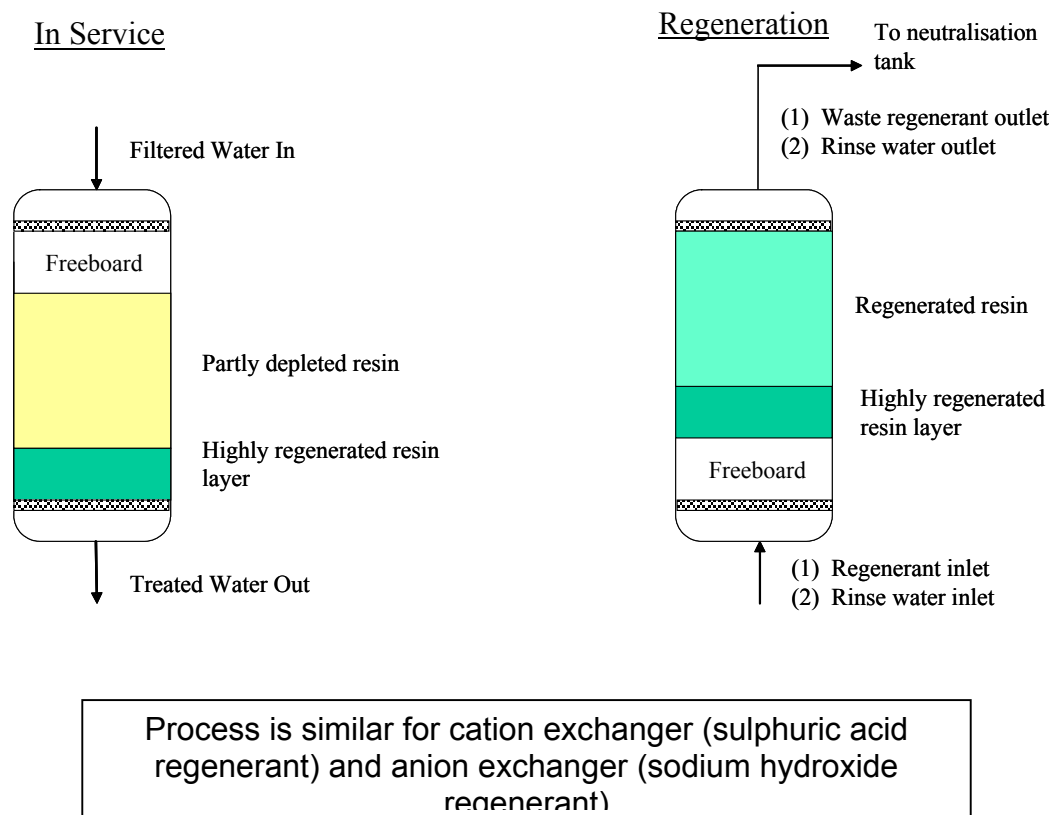
For those plants where the water flow is downward during exhaustion, regeneration can be in one of two directions. The early conventional method was to pass the regenerant through the resin in the same direction as the raw water. This is called co-current regeneration. It is simple but has the disadvantage that the ions at the top of the bed, which is the most highly exhausted region of the resin bed, are displaced towards the lower regions of the bed. Because economic conditions dictate that full regeneration cannot be achieved, some of these exchanged ions are retained in the lower part of the bed. During the next service cycle some of these retained ions are released into the treated water by the reverse action of equations (1) or (2). From the ion exchange equilibria and selectivity sequences the most common cation to show such leakage from a cation exchanger is sodium and the most common anion to leak from the anion exchanger is silica.

A more recent, but now well established technique is counter-current regeneration, where the regenerant is injected through the resin bed in the opposite direction to the flow of water during treatment. (Figure 3.3) The advantages are that the zone of the bed nearest the treated water outlet receives the highest regeneration level and is maintained in a highly regenerated state. This then limits the equilibrium leakage of ions from the raw water to very low levels, and in a well designed and operated system, it is possible to produce water of relatively high purity. Countercurrent regeneration can be applied to down-flow or up-flow service beds. In all cases it is necessary to maintain the outlet region of the bed in a highly regenerated form and this can only be achieved if the stratification of the bed remains undisturbed from one cycle to the next.

It has been necessary to develop methods of achieving this bed stability, particularly in the down-flow service/ up-flow regeneration configuration, where the up-flow of regenerant would tend to lift the bed and mix the lower layers of the resin bed. Therefore, a resin hold down or blocking procedure has to be included in the regeneration sequence. Two common systems have been developed, water hold down and air hold down. Both systems utilise a collector buried about 25-30cm below the top of the resin bed. In water hold down a water flow is introduced into the top of the bed and flows out of the buried collector. This asserts a downward pressure on the bed to counteract the tendency for the bed to rise when the regenerant is introduced in up-flow mode. This down-flow will continue at all times when regenerant or rinse water are flowing upward.

The second method is air hold down where the downward water flow is replaced by a pressurised air flow. This produces a dry crust of resin at the top of the bed which prevents the main bed from lifting and mixing during regenerant injection and rinsing.

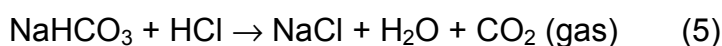
As the aim of counter-current regeneration is to maintain the resin in the bed outlet area in a highly regenerated state it is always good practice to use demineralised water to dilute the concentrated regenerants and also for primary, countercurrent, rinsing of the resins. This avoids introducing contaminants onto the freshly regenerated resins. If for some reason the resins at the bottom of the bed do become mixed, for example it may be necessary to backwash the whole bed, then the bed must be given a double regeneration, i.e. two successive regenerations, not a double strength regeneration, to restore the highly regenerated state of the bed outlet. Even then it may take several service cycles to restore the bed's performance to that prior to disturbance.



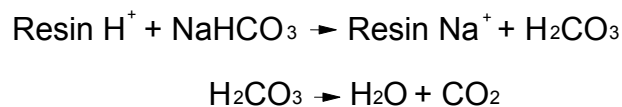
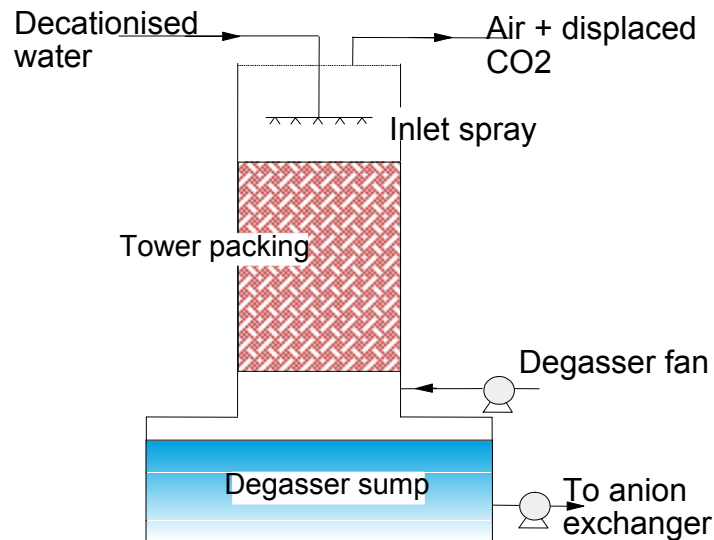
**Figure 3.3 : Downflow Service –Upflow Regeneration  
(Courtesy of E.ON UK)**

### 3.4 Atmospheric Degasser

Depending on the chemical composition of the raw water a degasser may be provided to reduce the ionic loading on the anion exchange resins. As noted in equation (1) the water leaving the cation exchanger is acidic. This will react with bicarbonates in the raw water to produce carbon dioxide (5).



The carbon dioxide is held in solution as a gas, but can be displaced by passing the acidic water down a tower with a high surface area packing in which air is continually blown in countercurrent mode. A typical atmospheric degasser is shown in Figure 3.4. Two 100% duty degasser fans are normally provided.



**Figure 3.4 : Typical Atmospheric Degasser  
(Courtesy of E.ON UK)**

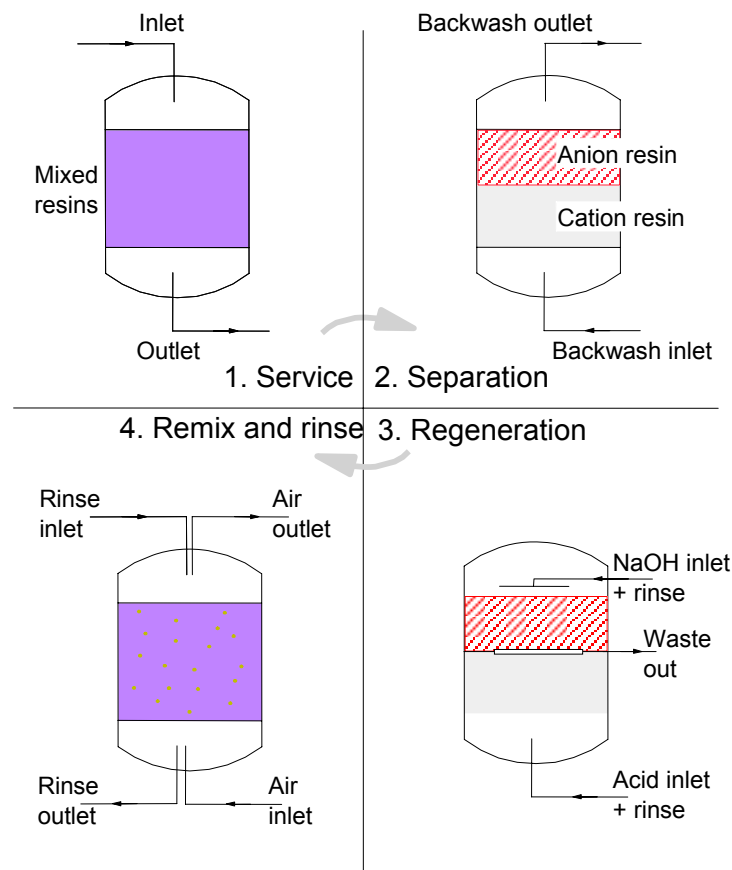
### 3.5 Mixed Bed Ion Exchanger

A mixed bed ion exchanger contains an intimate mixture of cation and anion exchangers which act as a whole series of successive cation and anion exchange stages, with the end product being very high purity water. The mixed bed is much more complicated than a single resin vessel containing a single exchanger. Within the vessel is contained the method for separating the two resins prior to regeneration, sets of distributors for injecting and collecting two different regenerants and a system for remixing the resins prior to return to service.

Resin separation is carried out by backwashing the resins with an up-flow of water. The resins will separate because the anion exchanger is of slightly lower density than the cation exchanger. In some systems the cation exchanger will be of a slightly coarser size grading than the anion exchanger, also assisting separation. The backwash velocity has to be sufficient to raise the whole bed but must not be so high that part of the resin is forced into the roof of the vessel. Mixed beds generally have more freeboard above the resins than normal single resin vessels to allow for this separation.

The mixed bed has three or four sets of collectors/distributors within the vessel. From the top these are the water inlet, the sodium hydroxide distributor (the first two may be combined), the centre collector at the interface of the settled, separated anion and cation exchangers, the bottom collector for treated water outlet, regenerant inlet and inlet for mixing air.

It is important during regeneration (Figure 3.5) to minimise the contact of a regenerant with the wrong resin. This can be done in several ways. The sodium hydroxide for anion exchanger regeneration is normally passed in at the top of the vessel and out via the centre lateral. There may be a blocking flow of water passing up through the cation exchanger to prevent sodium hydroxide passing onto the cation resin. Alternatively, the sulphuric acid for the cation exchanger regeneration may be passed upward through the cation resin and out of the centre lateral concurrently with



**Figure 3.5 : Mixed Bed Regeneration  
(Courtesy of E.ON UK)**

the sodium hydroxide injection.

## 4 OVERVIEW OF MEMBRANE SEPARATION TECHNOLOGY

The development and application of membrane separation processes is one of the most significant recent advances in chemical process engineering. Membrane processes are advanced filtration processes which utilise the separation properties of finely porous polymeric or inorganic films. Membrane separations are used in a wide range of industrial processes to separate biological macromolecules, colloids, ions, solvents and gases.

Membrane separation systems utilise semi-permeable polymeric or inorganic membranes to separate an influent feed stream into two effluent streams known as the permeate and the concentrate or reject. The permeate is the portion of the fluid that has passed through the semi-permeable membrane. The concentrate stream contains the constituents that have been rejected by the membrane.

The various membrane separation technologies which currently exist can be categorised on the basis of the size of particles removed from a feed stream. There are four commonly accepted categories, based on the size of the material they will remove from a carrier fluid. These are Reverse Osmosis (RO), Nanofiltration (NF), Ultrafiltration (UF), and Microfiltration (MF). A comparison of these membrane processes is shown in Table 4.1 and Figure 4.1.

Membrane Process	Typical Pore Size	Typical Operating Pressure (Bar)
Microfiltration	0.02 - 4 $\mu$ m	<2
Ultrafiltration	0.02 – 0.2 $\mu$ m	1 - 10
Nanofiltration	< 0.002 $\mu$ m	5 - 35
Reverse Osmosis (Hyperfiltration)	< 0.002 $\mu$ m	15 -150

**Table 4.1 : Comparison of membrane separation characteristics**

Membrane separation processes have the following advantages over conventional separation technologies:

- Appreciable energy savings
- Environmentally benign compared to other chemical separation processes such as ion exchange
- Clean technology with operational ease
- Replaces the conventional processes like filtration, distillation, ion-exchange and chemical treatment systems
- Can produce high, quality product water
- Modularity of systems provides greater flexibility in designing systems.

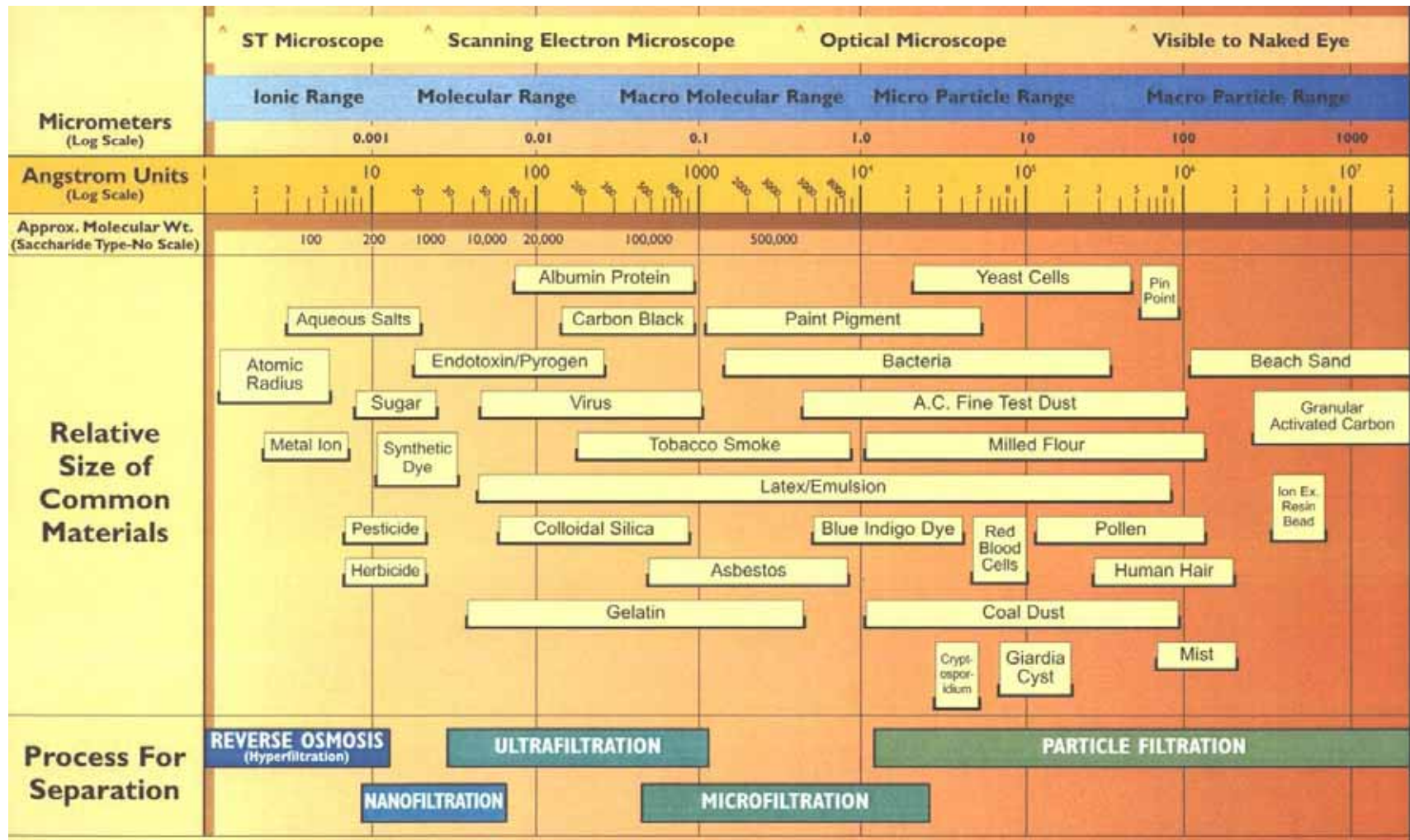


Figure 4.1 : Filtration Spectrum (Courtesy of GE)

#### **4.1 Cross-Flow Filtration with Membranes**

Conventional aqueous filtration using various filter media normally employ dead-end filtration in which all water flows perpendicularly through the filter media and any solids accumulate on the filter media surface.

Membrane filtration is the separation of the components of a pressurized fluid performed by polymeric or inorganic membranes. The openings in the membrane matrices (pores) are so small that significant fluid pressure is required to drive liquid through them; the pressure required varies depending on the size of the pores. Reverse osmosis (RO) membranes have the smallest pores, while microfiltration (MF) membranes have the largest pores, and hence, require the least pressure.

Crossflow filtration is the pressurized flow of the feedwater, or influent, across a membrane, with a portion of the feed permeating the membrane and the balance of the feed sweeping tangentially along the membrane surface to exit the system without being filtered. Because the feed and concentrate flow parallel to the membrane instead of perpendicular to it, the process is called "crossflow" or "tangential flow." Depending on the size of the pores engineered into the membrane, crossflow filters are effective in the range of reverse osmosis, nanofiltration, ultrafiltration and more recently microfiltration.

Crossflow membrane filtration allows continuous removal of contaminants, which under normal filtration would "blind" or plug the membrane pores very rapidly. Thus, the advantage of this design approach is that the membrane media is operated in a continuously self-cleaning mode, with solutes and solids swept away by the concentrate stream, which is running parallel to the membrane.

Unless membrane processes for reverse osmosis, nanofiltration and ultrafiltration applications are operated in a cross-flow mode of operation, they would not be viable water treatment technologies due to rapid irreversible fouling of the active membrane surfaces.

Microfiltration membranes have historically been operated in a dead-end filtration mode, requiring disposal of the membrane media due to blinding by the retained material. Some dead-end microfiltration systems employ an appropriate backwash procedure to remove accumulated material from the membrane surfaces.

#### **4.2 Reverse Osmosis**

Reverse osmosis, as its name implies, is a process whereby the natural phenomenon of osmosis is reversed by application of pressure to a concentrated solution in contact with a semipermeable membrane. If the applied pressure is in excess of the solution's natural osmotic pressure, the solvent will flow through the membrane to form a dilute solution on the opposite side and a more concentrated solution on the side to which pressure is applied. If the applied pressure is equal to the solution's natural osmotic pressure, no flow will occur. If the applied pressure is less than its natural osmotic pressure, there will be flow from the dilute solution to the concentrated solution.



The rate of water transport, commonly known as flux rate, across the membrane depends on the membrane properties, the solution temperature and the differential pressure across the membrane, less the difference in osmotic pressure between the concentrated and dilute solutions. Osmotic pressure is proportional to the concentration and temperature of the solution and also depends on the type of ionic species present. As a rule of thumb, the osmotic pressure of a solution predominantly of sodium chloride is 10psi per 1000mg/litre concentration.

Reverse osmosis is a membrane process specifically for the separation of dissolved ions from water. Charged ions and all other materials greater than or equal to .001 microns are rejected. Reverse osmosis membranes reject larger divalent ions, e.g.  $Mg^{2+}$ ,  $Ca^{2+}$ ,  $SO_4^{2-}$ , more effectively than smaller monovalent ions such as  $Na^+$  and  $Cl^-$ . Typically, rejection rates of >95% are achieved for divalent ions compared with 85% for monovalent ions. Thus, in practice, the main impurities in the permeate water are sodium and chloride. The rejection efficiency of silica is approximately 80%. Dissolved gases such carbon dioxide and oxygen are not removed by reverse osmosis.

All RO membrane systems require proper pre-treatment of the feed water to ensure reliable and trouble-free operation. RO membranes also require periodic chemical cleaning to restore and retain original operating specifications.

A common use for reverse osmosis is reduction or removal of dissolved ions alone or in combination with other technologies to produce ultra pure water for industrial and pharmaceutical applications, as well as processing sea water to potable water for city supplies.

### **4.3 Reverse Osmosis Membrane Materials**

The ideal reverse osmosis membrane has the following characteristics:

- High water flux rate
- High salt rejection
- Tolerant to chlorine and other oxidants
- Resistant to biological attack
- Resistant to fouling by colloidal and suspended material
- Inexpensive
- Easy to form into thin films or hollow fibres
- Mechanically strong e.g. withstands high pressures
- Chemically stable
- Able to tolerate high temperature

Commercial reverse osmosis membranes are manufactured principally from three type of materials; cellulose acetate, aromatic polyamide and thin film composites.

#### **4.3.1 Cellulose Acetate**

Cellulose acetate (CA) membranes are produced by casting a layer of cellulose acetate onto a porous substrate cloth which acts as a support to the cellulose acetate skin that

forms on air drying. The final CA membrane comprises of a thin CA layer of about 0.2µm on the more porous layer, which has an overall thickness of about 100µm.

Cellulose acetate (CA) membranes have poor chemical stability and tend to hydrolyse over time at a rate dependent on a combination of temperature and pH conditions. They can operate continuously in a temperature range of 0 – 30°C and a pH range of 4.0 – 6.5. The CA membranes are susceptible to biological attack, but this can be offset by their ability to withstand continuous exposure to low levels of chlorine. Due to their poor stability, CA membranes tend to suffer from deterioration in salt rejection with time. Despite these limitations, these membranes remain popular due to their wide availability and low cost.

#### 4.3.2 Aromatic Polyamide

Aromatic polyamide membranes are principally available in the form of hollow fine fibres. These fibres consist of a dense skin, approximately 0.1 to 1.0µm thick, formed on the outer surface with an inner porous supporting structure of approximately 26µm thickness.

Membrane made from aromatic polyamide are characterised by excellent stability, compared to cellulosic membranes. They can operate continuously at temperatures in the range 0 – 35°C and the pH range 4 – 11. The membranes are not subject to biological attack. However, they are susceptible to attack by chlorine and similar oxidants if continuously exposed. Therefore, it is necessary to dechlorinate the feedwater to the membranes.

#### 4.3.3 Thin Film Composites

Typically, the structure of thin film composite membranes comprise of an ultra-thin membrane barrier layer, approximately 0.2µm thick, formed on the surface of a microporous polysulphone layer which has been cast onto a porous fabric supporting layer. Typically, the membrane barrier layer on the polysulphone is created from various polyamides or polyureas.

The advantages of thin film composite membranes depend on the chemical composition and characteristics of the barrier layer. However, in general, they offer greater chemical stability and an ability to deliver high flux and high salt rejection at moderate pressures. They also are resistant to biological attack and can operate continuously at temperatures of 0 – 40°C and in a pH range of 2 -12. However, these materials do have a low resistance to chlorine and other oxidants.

### 4.4 Reverse Osmosis Membrane Modules

Reverse osmosis membranes are commercially available in spiral wound and hollow fibre configurations and, to a lesser extent, in tubular and plate and frame configurations. The following are desirable characteristics in a membrane device:

- Safe operation at high pressures
- No internal or external leakage
- Easy to flush and clean

- Minimal pressure drops
- Inert corrosion resistant materials
- Long term reliability of operation

#### 4.4.1 Spiral Wound Membrane Elements

Spiral wound membrane elements are made from flat film membranes that are wound around a perforated plastic centre permeate tube. Two or more leaves (permeate envelope) are attached to and wound around the centre tube. Each leaf consists of two membrane sheets supported and separated by a thin plastic net material. The edges of the leaf are sealed by special adhesives. A further plastic net spacer is also sandwiched between adjacent leaves to provide flow channels for the feed on the outside of the permeate envelope. The permeate passes through the membrane into the sealed envelope, where it spirals inwards to enter the centre tube through perforations and is then removed via the permeate outlet port. A typical spiral wound membrane is shown in Figure 4.2

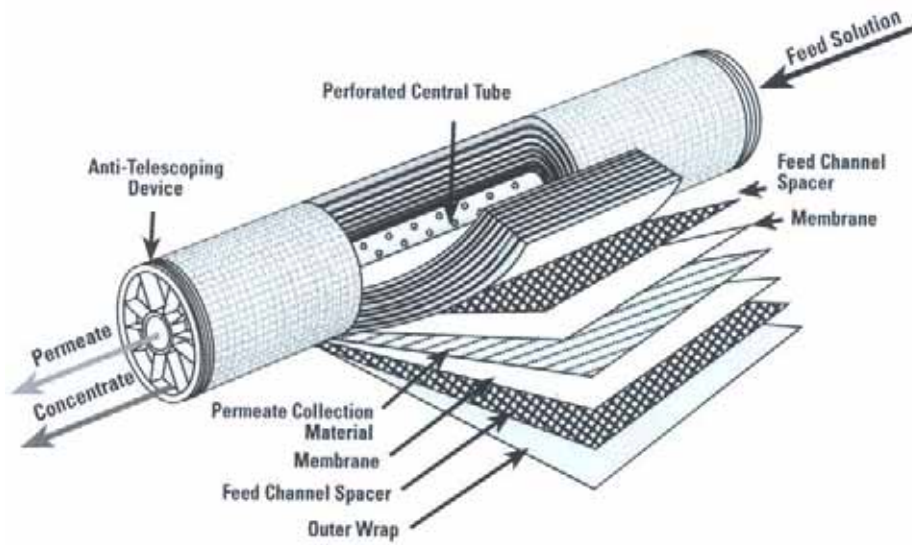
Individual spiral wound elements operate at approximately 8 to 10% recovery. Typically, four to seven elements are connected in series in a single pressure vessel to achieve up to 50% recovery. In this type of configuration, the slightly concentrated feed exiting one element feeds the next element. The permeate collection tubes for individual elements are connected together and the final discharge permeate is a blend from all the elements. The desired system capacity and recovery are achieved by connecting a number of pressure vessels in parallel.

The advantages of such systems are:

- Good resistance to fouling due to relatively open feed channels.
- Moderate- high membrane surface area to volume ratio
- Easy to clean
- Easy field replacement of elements
- Wide variety of membrane materials available.
- Several manufacturers

The main disadvantages are:

- Some tendency for concentration polarisation to occur.
- Difficulties in troubleshooting problems with individual elements in multiple element configurations

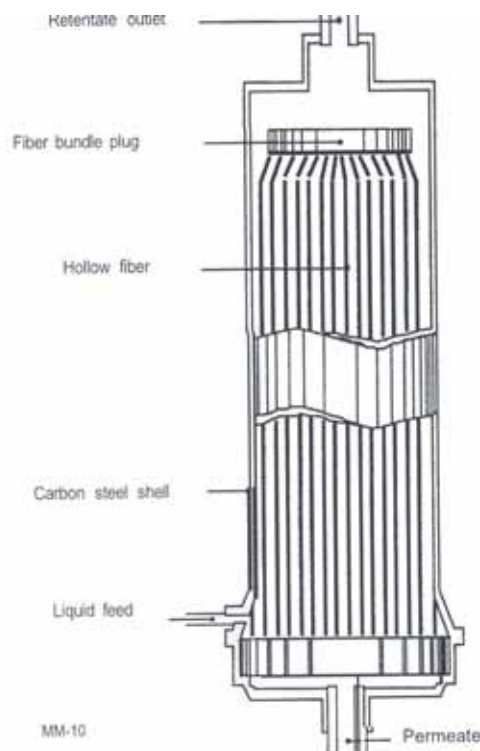


**Figure 4.2: Typical Spiral Wound Membrane Element  
(Courtesy of Koch Membrane Systems)**

#### 4.4.2 Hollow Fibre Membrane Element

Membrane elements based on hollow fibre technology are formed by orienting the fibres parallel to a perforated centre feed tube. The fibres are “potted” with special epoxy resins to create a tube sheet on one end and a “nub” on the opposite end. The tube sheet is then machined to expose the ends of the fibres. The feed and permeate stream are prevented from mixing by an O-ring. Unlike spiral wound element design, a pressure vessel typically contains only one fibre bundle element.

The pressurised feedwater is introduced into the centre tube where it is distributed along the entire length of the membrane element. The feedwater then flows radially outward around the outside of the fibres. The product water permeates through the fibre walls and into the bore before exiting through the tube sheet into the permeate outlet port. The concentrated feed flows between the outside of the fibre bundle and the inside wall of the pressure wall. Individual hollow fibre elements operate at approximately 50% recovery. A typical hollow fibre membrane element is shown in Figure 4.3.



**Figure 4.3 : Typical Hollow Fibre Membrane Element  
(Courtesy of US Environmental Protection Agency)**

The advantages of such systems are:

- High membrane surface area to volume ratio
- High recovery in individual elements
- Easy to troubleshoot
- Easy to change bundles in field,.

The main disadvantages of are:

- Sensitive to fouling by colloidal and suspended particulates.
- Limited membrane materials
- Small number of manufacturers

#### 4.4.3 Tubular Configuration

Tubular configurations were used in some of the earliest practical applications of reverse osmosis. However, these designs have rapidly been displaced by spiral wound and hollow fibre designs which offer greater membrane surface area to volume ratios at a lower cost. Thus, tubular configurations are no longer generally used for reverse osmosis water purification applications.

#### 4.4.4 Plate and Frame Configuration

The plate and frame designs originate from the early reverse osmosis applications. They utilise flat sheet membranes and are modelled on the design of plate and frame filter presses. The simplest stack design consists of several sets of alternating frames which support the membrane on the permeate side and separate the membranes on the feed side. The entire assembly is pressed between two end plates and held together with tie rods. The frames in addition to supporting the membranes, have flow channels that collect the permeate and direct it to a permeate manifold. The feed frames are connected in parallel by a feed manifold and contain a spacer material to separate adjacent membrane sheets and provide flow channels.

As with tubular membrane configuration, their applications in reverse osmosis are limited as they are not cost-effective as spiral wound and hollow fibre elements. However, this plate and frame configuration is widely used in electrolytic membrane applications such as electrodialysis and electrodeionisation.

The various configurations and characteristics of RO crossflow membrane elements available are summarised in Table 4.2.

Characteristic	Traditional Spiral Wound	Spiral Wound	Hollow Fibres	Tubular	Plate & Frame
Cost	Low	Low-Med	Low	High	High
Packing Density	High	Moderate	Very High	Low	Moderate
Pressure Capability	High	High	High	Medium	High
Membrane Polymer Choices	Many	Many	Few	Few	Many
Fouling Resistance	Fair	Good	Poor	Very Good	Fair
Cleanability	Fair	Good	Poor	Good	Fair

**Table 4.2: Crossflow Membrane Configuration Comparison**

## 4.5 Other Membrane Separation Technologies

### 4.5.1 Nanofiltration

Nanofiltration (NF) is typically referred to as a "loose" RO due to its larger membrane pore structure as compared to the membranes used in RO. Thus, it allows more salt passage through the membrane. NF membranes also have a strong rejection of divalent ions over monovalent ions with typical salt rejection rates of 95% for divalent salts and 40% for monovalent salts. It rejects various larger sized organic molecules, including dyes, sugars as well as naturally occurring organics present in surface waters.

Nanofiltration generally uses spiral wound membranes configured in a similar design as reverse osmosis. Membranes used for NF are of cellulose acetate and aromatic polyamide type. As NF can operate at much lower pressures, and passes some of the inorganic salts, it is used in applications where high organic removal and moderate inorganic removals are desired.

An advantage of NF over RO is that NF can typically operate at higher recoveries, thereby conserving total water usage due to a lower concentrate stream flow rate. NF is not effective on small molecular weight organics, such as methanol.

Some applications include partial softening of feed water, removal of contaminants from water or acid streams, and occasionally pretreatment for reverse osmosis or other high purity systems.

### 4.5.2 Ultrafiltration

Ultrafiltration is a membrane process that separates colloidal material, emulsified oils, micro biological materials, and large organic molecules. The range of separation is generally 10,000 to >80,000 molecular weight cut-off.

Ultrafiltration is most commonly used to separate a solution that has a mixture of some desirable components and some that are not desirable. UF is somewhat dependent on charge of the particle, and is much more concerned with the size of the particle. Typical rejected species include sugars, bio-molecules, polymers and colloidal particles. The driving force for transport across the membrane is a pressure differential. UF processes operate at 2-10 bars, though in some cases up to 25-30 bars have been used. UF processes perform feed clarification, concentration of rejected solutes and fractionation of solutes.

Ultrafiltration membranes are made from a wide range of more rugged polymers, since their larger pore size and "sieve" mechanism of separation allow more material choices. Cellulose acetate, polyvinylidene fluoride, and especially polysulfone are the most common. Polysulfone UF membranes can withstand a pH range of 0.5 to 13, temperatures to 85°C and 25mg/L of free chlorine on a continuous basis.

A summary of the operating conditions for various membrane types commonly used in RO and UF applications is provided in Table 4.3.

<b>Class</b>	<b>Polymer Type</b>	<b>Max Temp (psig)</b>	<b>Max Pressure (psig)</b>	<b>Optimum pH Range</b>	<b>Max Free Chlorine Continuous (ppm)</b>
RO/NF	Cellulose Acetate (CA)	40	1000	2-8	2
	Polyamide (PA)	65	1000	2-11	< 0.1
UF	CA	60	200	2-9	3
	Polysulphone (PS)	100	200	0.5-13	25
	Vinylidene fluoride (VF)	80	200	1-12	50
	Acrylonitrile (AN)	80	200	1-10	50

**Table 4.3 Operating parameters for widely used polymeric RO and UF membranes.**

#### 4.5.3 Microfiltration

Microfiltration (MF) is a membrane process that separates suspended solids and some colloidal materials (>0.1 micron) from a feed stream. The concentrate (material that does not pass through the membrane) requires periodic removal or cleaning to prevent the eventual plugging of membrane feed passageways.

The primary uses of microfiltration involve separation of specific suspended solids, and substitution for standard clarification systems using chemical precipitation processes.



A MF membrane is generally porous enough to pass molecules of true solutions, even if they are large. Thus, they are not effective in removing dissolved organic matter from surface waters. Microfiltration membranes can also be used to sterilize solutions, as they are prepared with pores smaller than 0.3 microns, the diameter of the smallest bacterium, *Pseudomonas diminuta*.

While the mechanism for conventional depth filtration is mainly adsorption and entrapment, MF membranes use a sieving mechanism with distinct pore sizes for retaining larger size particles than the pore diameter. Hence, this technology offers membranes with absolute rating, which is highly desirable for critical operations such as the preparation of particulate free water.

The MF membranes are made from natural or synthetic polymers such as cellulose nitrate or acetate, polyvinylidene difluoride (PVDF), polyamides, polysulfone, polycarbonate, polypropylene, PTFE etc. The inorganic and ceramic materials such as metal oxides (alumina), glass, zirconia coated carbon are also used for manufacturing the MF membranes.

#### 4.5.4 Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Electrodialysis (ED) and electrodialysis reversal (EDR) are membrane processes in which water flows between a series of alternative cationic and anionic membranes located between two electrodes. Ionic impurities contained in the feed water are drawn through membranes by the application of a direct current, instead of being forced through by pressure. In ED, the polarity of the electrostatic field remains unchanged, whilst in EDR, the polarity is alternated periodically to prevent the accumulation of scale or colloidal species on the membrane surface.

Under the influence of the direct current, cations present in the water being positively charged move towards the anode. Similarly anions will move to the cathode. As the cations can only freely pass through the cation membranes and anions can only pass through the anion membrane, the salts present in the water become concentrated and depleted in alternate compartments.

An ED/EDR membrane stack consists of several hundred cell pairs mounted between two platinised electrodes. Each cell pair comprises a cation transfer membrane, a diluate spacer, an anion transfer membrane and a concentrate spacer. A single pass of water through a stack will produce a salt removal efficiency of 30 -60%, depending on temperature, flow rate, applied voltage and chemical composition of the water.

Of the two applications, ED is the more commonly used at present. However, both processes require a relatively high quality feedwater and neither can tolerate high levels of silica or organics. Therefore, ED and EDR are only really suitable for final polishing applications at the present time.

#### 4.5.5 Continuous Electrodeionisation (CEDI)

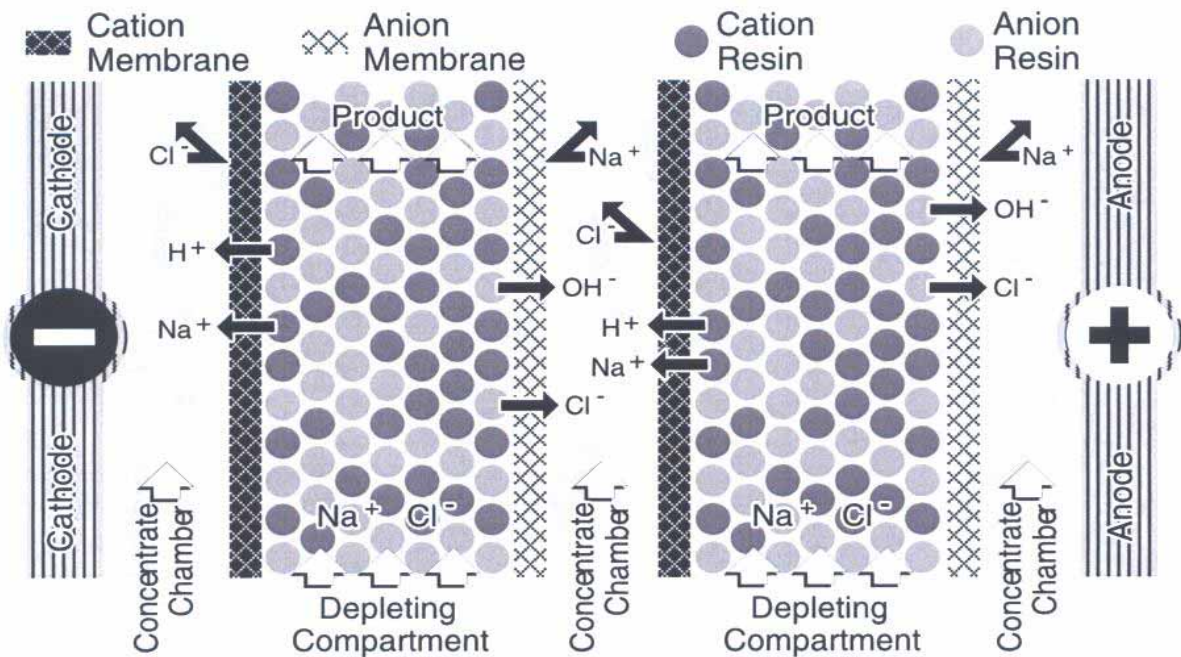
Continuous Electrodeionisation (CEDI) is the process of removing ionised species from water using a combination of ion exchange membranes, ion exchange resins and a DC

electric potential. It is similar to the ED/EDR process except that CEDI incorporates the use of ion exchange resins.

Most CEDI systems comprise alternating cation and anion permeable membranes with spaces in between configured to create liquid flow compartments with inlets and outlets (Figure 4.4). The compartments bound by an anion membrane facing the positively charged anode and a cation membrane facing the negatively charged cathode are diluting compartments. The compartments bound by an anion membrane facing the cathode and a cation membrane facing the anode are concentrating compartments.

To facilitate ion transfer in low ionic strength solutions, the dilute compartments are filled with ion exchange resins. A transverse DC electrical field is applied by electrodes at the bounds of the membranes and compartments. When the electric field is applied, ions in the water are attracted to their respective counter electrodes. The result is that the diluting compartments are depleted of ions and the concentrating compartments are concentrated with ions.

There are various types of CEDI systems available but they are all of similar design, being either based on spiral wound or plate and frame design. The CEDI process has similar limitations as ED/EDR in that it requires a relatively high quality feedwater and is best applied as a polishing treatment



**Figure 4.4 ; Continuous Electrodeionisation Process (Courtesy of EPRI)**

## **5 CURRENT STATUS OF THERMAL DESALINATION TECHNOLOGIES**

The most widely used thermal desalination processes for the production of potable quality water from seawater are multistage flash evaporation (MSF), multiple effect distillation (MED) and mechanical vapour compression (MVC). The MSF process dominates the worldwide market for both brackish water and seawater desalination.

### **5.1 Thermal Desalination Process Options**

All three types of thermal desalination are equipped with condenser tube bundles. In MSF, these are used to preheat the brine recycle stream. The tube bundles in MED and MVC function as condensers/evaporators, where the heating steam condenses inside the tubes and vapour is formed outside the tubes. The MED and MVC are divided into evaporating effects while MSF systems are divided into flashing stages.

All of the systems employ a number of large pumping units, including pumps for seawater intake, distillate product, brine blowdown and chemical dosing. The MSF and MED systems have additional pumps for the cooling seawater. In addition, MSF has pumps for brine recycle.

Both MSF and MED require steam, normally extracted from low/medium pressure turbines or package boiler, to provide the heat necessary for flashing or evaporation.

The MSF process operates with a maximum brine temperature of in the range 90 – 110°C. The MED and MVC processes are operated with lower maximum temperatures in the range 64 – 70°C.

MVC is distinguished from the other processes by the presence of a mechanical vapour compressor, which compresses the vapour formed within the evaporator to the desired pressure and temperature.

The capacity of thermal desalination processes varies over a wide range, from 500m<sup>3</sup>/day to 55,000m<sup>3</sup>/day. Typically, the average conventional sizes are 3000m<sup>3</sup>/day for MVC, 33,000m<sup>3</sup>/day for MSF and 12,000m<sup>3</sup>/day for MED.

### **5.2 Comparison of Thermal and Reverse Osmosis Desalination Technologies**

An advantage of thermal distillation processes is the potential for economies of scale although this is unlikely to be realised with smaller capacity plant that would be required for a typical power plant. Distillation plant also tends to be significantly more costly than equivalent capacity reverse osmosis (RO) plant.

Whilst RO plant have greater pretreatment requirements, distillation plant are energy intensive and generally have lower recovery rates than RO systems. Distillation plant based on the MSF and MED processes also require a steam supply.

The RO membrane process has a simple layout, is compact and modular. Thus, RO installations have a very high production capacity/space ratio and require less surface area than distillation plant of similar capacity. However, RO membranes are more sensitive to the conditions of the feed seawater, scaling, fouling and pH than thermal processes. Pretreatment of the seawater to remove suspended solids is also required.

Furthermore, unlike thermal processes, RO membranes do not provide high purity water. On average, the permeate salinity can vary over the range 100 – 500ppm for a single pass system. The actual value depends on the water temperature and permeate recovery. Depending on the quality of the permeate, a second RO pass may be needed followed by further treatment by either mixed bed ion exchange or electrodeionisation to achieve the required quality of deionised water necessary for the power plant..

Thermal distillation plant produce a much higher purity water than RO plant and water containing total dissolved solids of 10mg/litre can be produced. However, this quality is still unsuitable for use within the power plant steam generators and further treatment would be necessary to attain deionised water quality.

Due to the use of high pressure pumps, average power consumption in an RO desalination plant is in the range of 5kWh/m<sup>3</sup>. However, energy consumption can be further reduced through the use of energy recovery systems.

Energy requirements for the MSF and MED thermal processes are higher than those for MVC and RO systems. MSF and MED consume substantial quantities of energy in the form of heating steam to drive the flashing and evaporation processes. In addition, they also use considerable amount of electrical power, to drive the associated pumps. Typically, the average power consumption is 4kWh/m<sup>3</sup> of product water. Steam requirements for these processes range from 0.1 to 0.5kg/m<sup>3</sup> of distillate. The MVC process does not require any steam and its power consumption is in the range 6 – 10kWh/m<sup>3</sup> of product water.

Due to the high energy requirements, in terms of both steam and power, thermal desalination is most widely used in the Middle East region, where both thermal and electrical energy is abundant and inexpensive to produce. Although, historically some older UK and US power plant have used evaporators as an initial stage in the production of deionised make-up water, these processes have been superseded primarily due to scaling and corrosion problems experienced and the overall economics of the process due to the high costs of energy.

Seawater desalination by reverse osmosis remains the lowest cost method of desalination in a stand-alone process. However, when a thermal desalination process is integrated with power generation the overall energy efficiency of this combined process is much higher than when generating electricity and desalting seawater as separate processes. Such combined processes are predominantly used for the production of potable water quality supplies from saline water sources in either arid areas or areas where there are insufficient potable water supplies from natural sources. Production of water for the sole use of the power plant is at present not realistically economical or efficient. Hence, for many power plant that are unable to source water of

acceptable quality for use in the make-up water production process, the adoption of RO desalination represents the best practicable and cost-effective option.

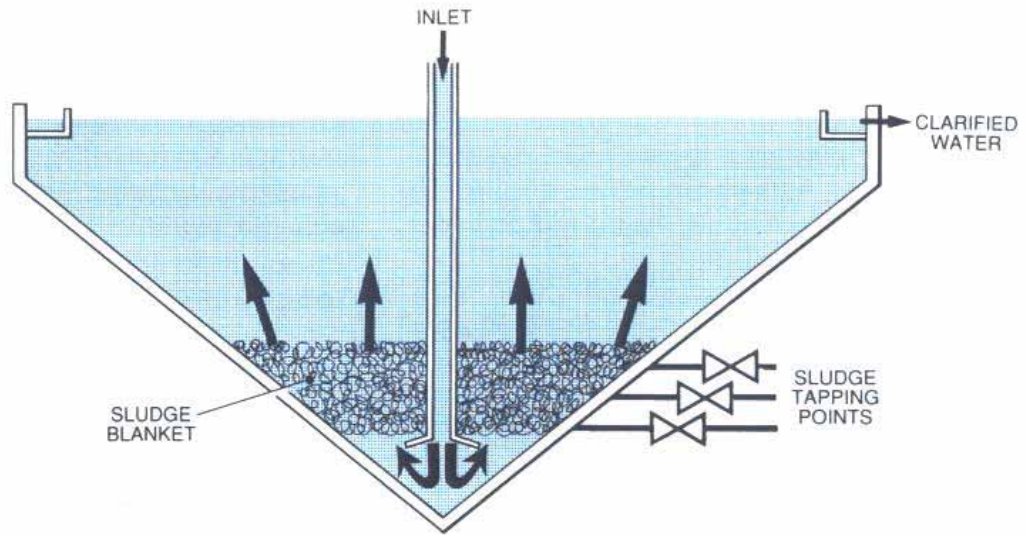
## **6 CURRENT STATUS OF WATER PRETREATMENT TECHNOLOGIES**

### **6.1 Clarification**

The clarification of water is a process applied mostly to surface waters for the removal of suspended solids, finely divided particles present as turbidity or colour, and other colloidal materials. Conventionally, the clarification process involves coagulation, flocculation and sedimentation reactions. The aim of coagulation and flocculation is to produce particles of a size that can be removed by settlement, flotation, or filtration. Particles present in water tend to have similar negative electrical charges and the repulsive forces keep the particles separate, impeding settlement. In coagulation, chemicals providing metal ions, such as aluminium and ferric salts, are dosed to destabilise the repellent electrical forces, enabling particles to coalesce to form small floc. This process occurs very rapidly. Flocculation is the longer-term process of forming larger and heavier particles from the small particles formed during coagulation to facilitate removal by physical processes. Polyelectrolytes (cationic, anionic or non-ionic polymers) are often used as flocculant aids, usually following a primary inorganic coagulant. These additives promote the aggregation and binding of particles, leading to more rapid settling. Flocculated solids are generally removed from the wastewater by sedimentation, which relies on gravity to separate the flocculated sludge. There are a number of factors that can affect the coagulation/flocculation process. The most important of these is pH where, for a given coagulant, there is usually an optimum pH at which coagulation/flocculation is most effective.

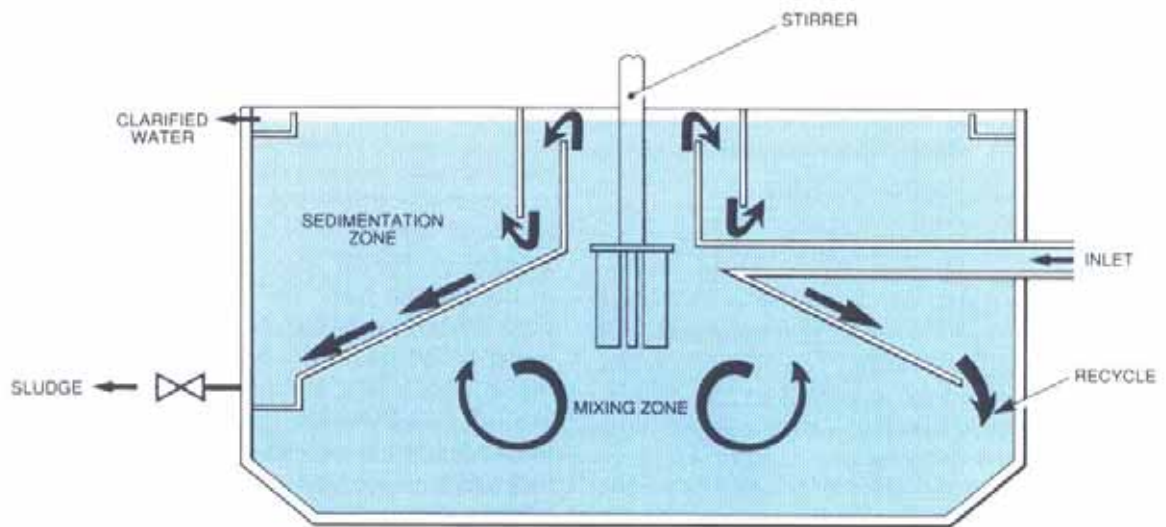
One common form of pre-treatment clarification in power plant is the clarifier, which is a large diameter steel or concrete circular tank. The chemicals are mixed with the raw water which flows slowly upwards from the bottom of the tank to overflow into collection weirs at the top. Dependent upon the design the large flocs either settle to the floor of the tank, which is coned towards the centre, or they form a sludge blanket layer, in which the tendency of the blanket layer to fall is counteracted by the up-flow of water. In the first case sludge is collected from the bottom of the tank, in the second it is tapped off from the height of the blanket. The sludge blanket treatment is particularly effective at trapping suspended solids, fine particulates and colloids. The clarified water is then filtered by filters to remove any small floc particles that may have been carried over.

A variety of clarifiers designs are available for pre-treatment clarification and some are shown in Figures 6.1 and 6.2.



(a) Hopper bottom sedimentation tank

**Figure 6.1 : Hopper Bottom Sedimentation Tank  
(Courtesy of BEI)**



(b) Sludge re-circulation tank

**Figure 6.2 : Sludge Recirculation Tank  
(Courtesy of BEI)**

An alternative approach is to inject the coagulant upstream of sand filters with enough residence time in the pipework to allow floc formation. The floc formed is then collected on the filters. This process is known as in-line coagulation. Flocculant aids can also be fed in a similar manner to improve filtration efficiency and increase filter operational service cycles. Rapid dispersion of the coagulant in the flowing water is important and this is commonly accomplished through the use of an in-line static mixer

Typical coagulants are the chlorides or sulphates of iron or aluminium, sodium aluminate and polyaluminium chloride. Under optimum conditions, these form dense voluminous flocs of iron or aluminium hydroxides. The choice of coagulant depends on the particular characteristics of the raw water. Flocculation aids are generally acrylate based organic polymers.

## **6.2 Filtration**

Filtration is a basic process for separating fluid/solid mixtures by passage through a porous filter medium which treats a percentage of the suspended solids. The fraction of solids retained by the filter depends on the pore size of the medium and the dimensions of the particle to be removed.

Granular filters, also referred to as deep bed filters, are available in two basic designs; gravity or pressure filtration. In gravity filtration, water flows through the filter medium contained in an open tank or vessel under the influence of gravity. In pressure filtration, the filter medium is held in enclosed pressure vessels and the water is pumped through the filter medium under pressure. Gravity filters produce better quality water compared to pressure filters but their space requirements/footprint are much more than that required for pressure filters of the same capacity. Pressure filters may be of either a horizontal or vertical design. Pressure filters tend to be the preferred choice for power plant applications.

Standard media used in deep bed granular system includes anthracite, coarse silica or quartz sand, fine sand and high density garnet. Filters can be employed with a single medium (typically sand), a dual medium (sand and anthracite) or multi-media (sand, anthracite and garnet). Multi-media filters are generally graded and layered with granule size decreasing and density increasing from top to bottom. This allows the entire depth of the filter to be used to remove solids, rather than just the top surface, as often occurs during the operation of single media filters. Multi media filters offer higher filtration efficiency due to the different filtering media having different filtration properties. The disadvantage is that if the layer structure of the media is disturbed the filtration efficiency will be reduced. Therefore, these types of filters incorporate a re-stratification stage which often requires quite high water velocities.

Solids are removed from filter beds by scouring and backwashing with air and water, which produces a waste sludge for disposal or treatment. Generally, backwashing of granular filters is undertaken as a batch process after each filter has treated a fixed volume of water or a maximum differential pressure across the filter bed has been attained. However, there are some novel designs of granular filter including a system in which the media filter is continuously backwashed.

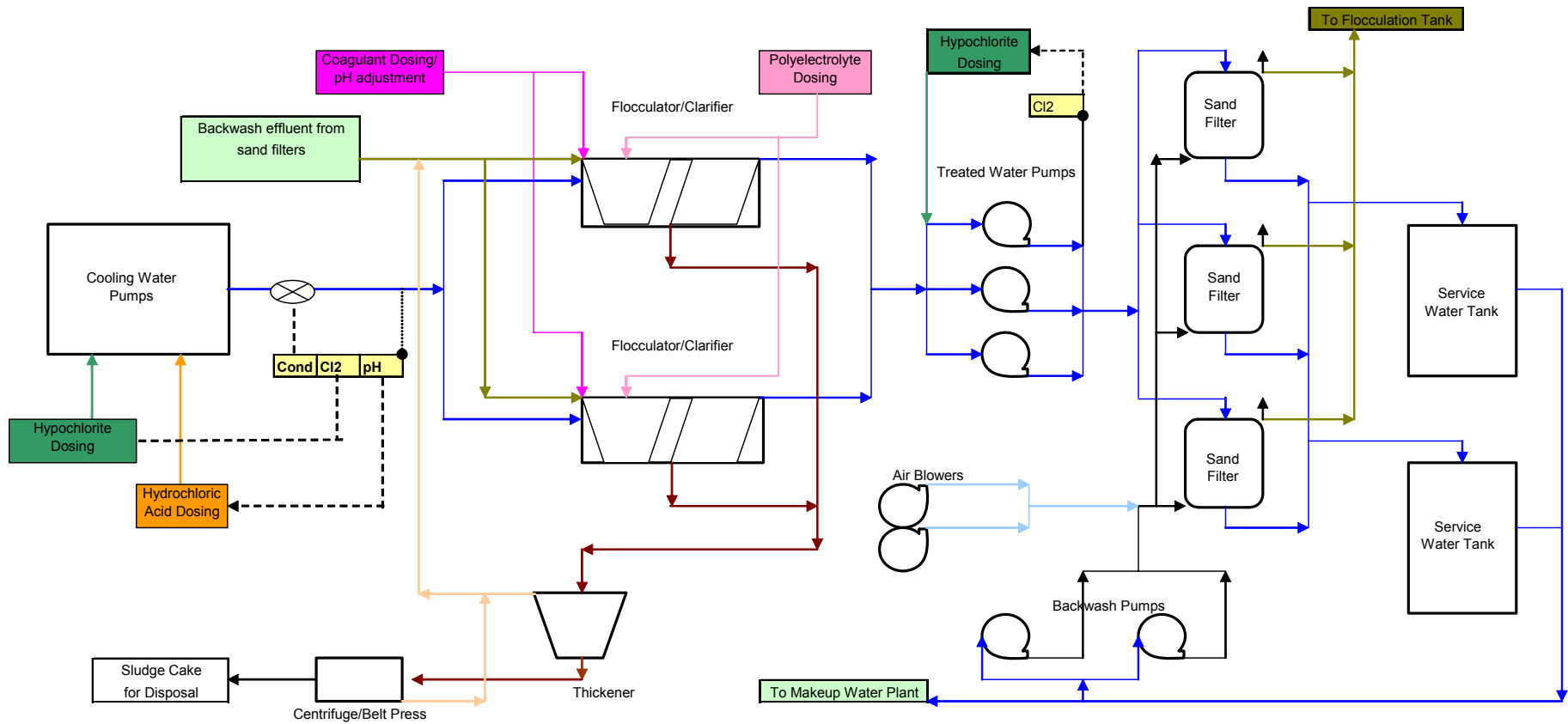


Single or multimedia filtration systems are used widely in water treatment plant applications for the removal of suspended solids. Typically, waters containing less than 30mg/litre of suspended solids can be effectively treated with single medium filters. For suspended solids levels between 30 – 50mg/litre, dual media is the preferred choice. Higher suspended solids loadings can be effectively treated by multi media filters.

Filtration almost always follows a clarification stage to remove small floc particles carried over from the clarifier and is also used frequently as a pre-treatment step before reverse osmosis units. However, for reverse osmosis applications granular filtration is incapable of removing fine or colloidal particles and a second stage of filtration is required to prevent fouling of reverse osmosis membranes. Normally cartridge filters with a nominal porosity of 5 to 10 microns are used for this purpose. Cartridge filters may be either replaceable element or cleanable, backwashable types.

At present, multi-media granular filters are the most widely utilised in power station water treatment plants, although membrane technologies, such as microfiltration are becoming increasingly more common. A typical conventional clarification and filtration process for treating river water is shown in Figure 6.3,

Typical capital costs for a conventional clarification and filtration plant can range from £1.3 – 3.5 million for plants treating 15 to 100m<sup>3</sup>/hour respectively. Due to the large variety of coagulant and flocculant chemicals available for use in these processes and the variability in water quality, it is not possible to provide typical operating costs.



**Figure 6.3 ; Process Diagram for Conventional Clarification and Filtration for Treatment of River Water (Courtesy of E.ON UK)**

### 6.3 Membrane Microfiltration

Membrane microfiltration removes virtually all suspended and some colloidal matter. Increasingly, membrane microfiltration is successfully replacing conventional clarification processes in a number of applications, particularly in the area of municipal water treatment.

However, there is no long term experience of their use in UK power plants. Similarly, worldwide, the application of polymeric membrane microfiltration is widespread in many industrial sectors but there has, until recently, been limited experience with this technique within the power sector. Ceramic membrane microfiltration systems are also available but their use is limited relative to the polymeric membrane systems. Ceramic filter elements are compatible with chemicals added to promote flocculation and can resist aggressive chemical cleaning procedures.

The hollow fibre has established itself as the best configuration for membrane microfiltration because its self-supported, back-washable structure is ideal for building compact, large surface area modules. Membrane microfiltration can be operated either as crossflow or dead-end filtration. Dead-end filtration has two streams; feed water inlet and permeate. 100% of the feed water passes through the membrane. In crossflow filtration, there are three streams - inlet feed water, reject concentrate and permeate. Thus, in crossflow filtration, water recovery is not 100%.

There are essentially two different configurations in terms of water flow, either outside-in or inside-out. For the outside-in configuration, there is more flexibility in the amount of feed to flow around the hollow fibres, whereas inside-out configurations have to consider the pressure drop through the inner volume of the hollow fibres. Inside-out configuration, however, offers much more uniform flow distribution through the bore of the hollow fibre compared to its counterpart configuration. Crossflow microfiltration systems operate at high recovery and flux rates and backwashing and air scouring techniques are frequently utilised to reduce fouling. A typical pressurised microfiltration membrane system is shown in Figure 6.4.

If chlorine resistant membrane materials are used, e.g. polysulphone or ceramic, chlorine can be added to the feed water used to retard biological fouling

The key objective in designing a hollow fibre system is to maximise filtration surface area at the lowest possible cost. By filtering from the outside of the fibre to its inside, the filtration surface in contact with the feed water is increased by the ratio of outside to inside diameter, typically a factor of 1.5 to 2.5. Additionally, as the filtration surface per unit module volume is inversely proportional to the hollow fibre diameter, reducing hollow fibre diameter by a factor of two can double the surface area in the same footprint without increasing the amount of membrane material used. However, decreasing fibre diameter to improve material efficiency must be balanced against the consequential internal pressure loss and higher manufacturing costs associate with shorter fibre length.

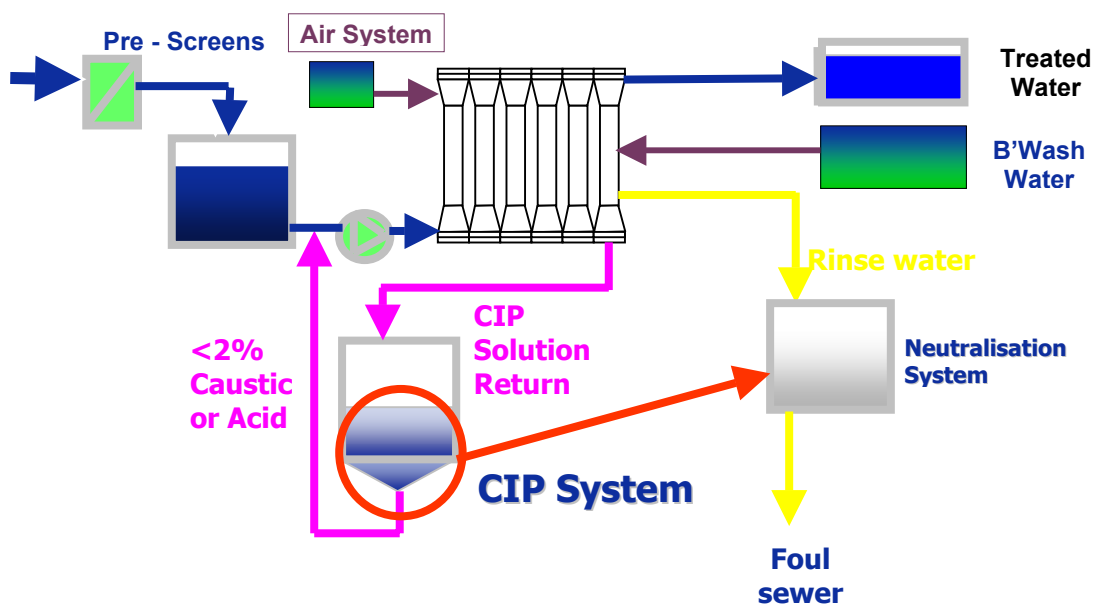
Whilst, some earlier membrane microfiltration designs utilised crossflow or tangential filtration to reduce fouling, later designs have abandoned this approach and have adopted dead-end filtration to reduce energy consumption from recirculation pumps.

However, this mode of operation leads to additional hydraulic resistance from an accumulated filtration cake on the membrane surface and correspondingly high trans-membrane pressures. Experience has shown that the most effective approach to reduce energy consumption for a given flow is to operate in dead-end mode with maximum membrane surface area to limit the rate of cake growth, thereby reducing the requirements for higher pressures, continual shearing of the membrane surfaces and frequent backwashes.

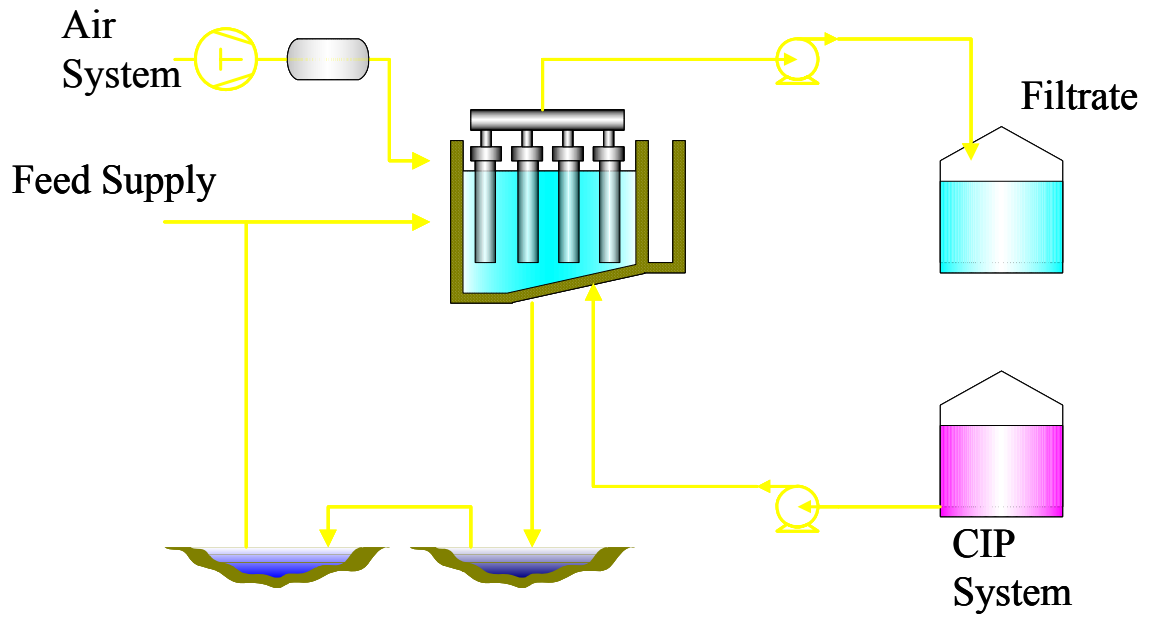
Current designs now have more membrane surface area which allows systems to be operated under gentler conditions with lower pressures, lower cyclical stresses associated with backwashing operations, lower fouling and lower chemical cleaning frequency.

A further development in microfiltration membrane technology has been the use of immersed hollow fibre membranes as opposed to the use of hollow fibre and spiral wound configurations in pressurised vessels or shells. Immersed membranes differ from pressurised membranes in that pressure vessels are not used to hold the membranes (Figure 6.5). Instead, shell-less hollow fibres are immersed into a tank open to the atmosphere and a gentle suction is applied to draw clean through the fibres.

Through the use of open tanks, immersed membrane systems save of the cost of pressure vessels. Furthermore, through the use of low trans-membrane pressures, i.e. suction, fouling of the membranes can be minimised.



**Figure 6.4 : Typical Membrane Microfiltration Pressurised System (Courtesy of Memcor)**



**Figure 6.5 : Typical Membrane Microfiltration Immersed System  
(Courtesy of Memcor)**

## **7 CURRENT STATUS OF ION EXCHANGE PROCESSES FOR DEIONISED WATER PRODUCTION**

Ion exchange technology has typically been an integral part of the makeup water treatment system of fossil fired power plant. In makeup water treatment the primary objective is usually to remove all ionic impurities from the raw water supply. This process of removing these ionic impurities is commonly referred to as demineralisation or deionisation.

The main components in an ion exchange water treatment plant are the ion exchange units, the regenerant storage and handling facility, the control system and the effluent neutralisation system. For many plants, a degasser will be installed to remove carbon dioxide produced after the cation exchange stage.

The type of ion exchange process required to produce makeup water for a fossil fuel power plant depends on a number of factors:

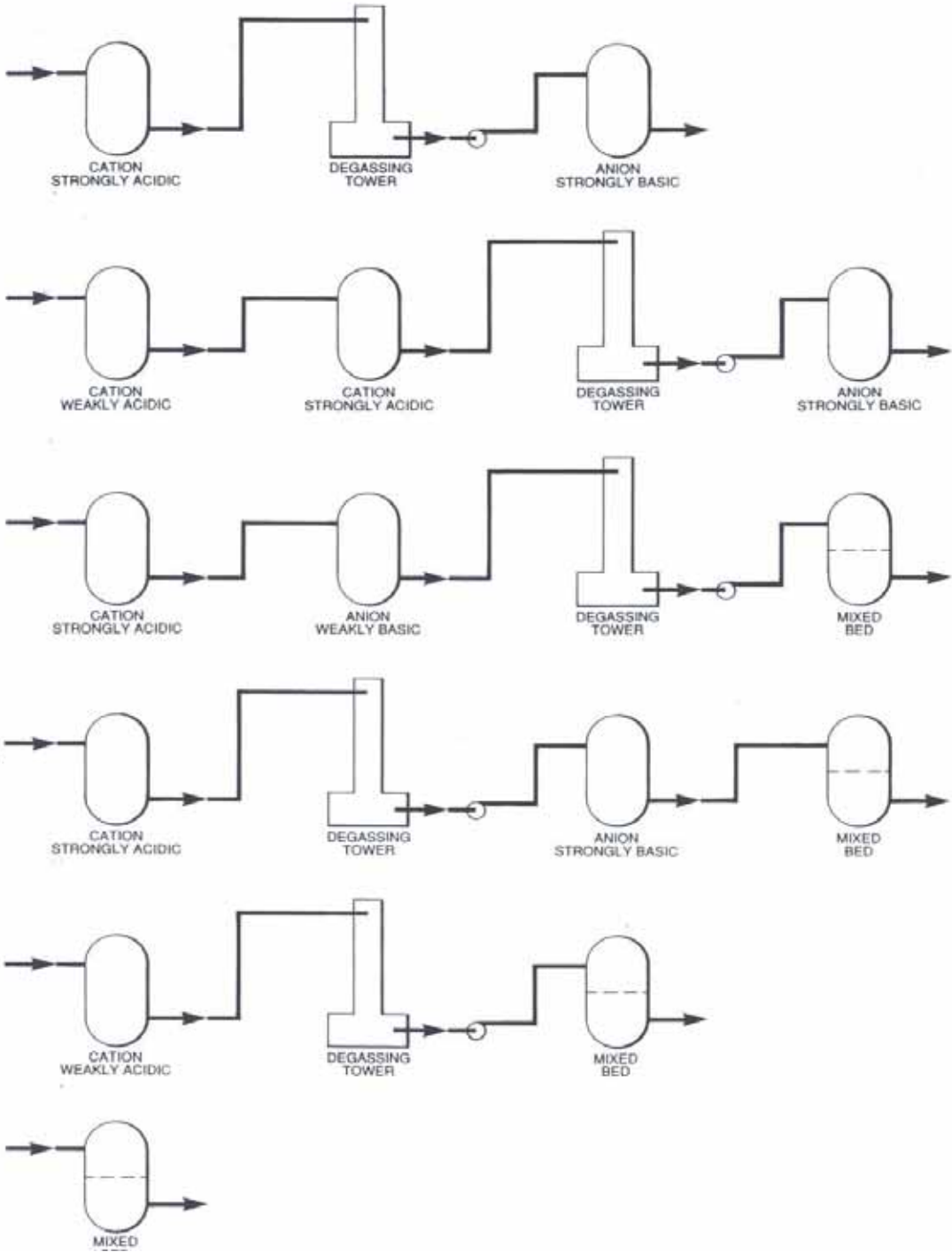
- The chemical composition of raw water being supplied to the makeup water treatment plant.
- The degree of pre-treatment the raw water has previously undergone.
- The purity of treated makeup water required by the steam/water cycle of the boiler.
- The quantity of makeup water to be produced.
- The capital cost of the plant.
- The operating costs of the plant.

The purity required for cycle makeup depends to a large extent on the type and pressure of the boiler plant. For low pressure boilers, i.e. < 60 bar, a single stage mixed bed unit would be the most basic of plant capable of producing an acceptable makeup water quality. The mixed bed unit contains a mixture of strong acid cation resin and strong base anion resin in the hydrogen and hydroxide form respectively. Alternatively, single cation and anion units in series, whilst producing slightly lower quality water, would still produce makeup water of adequate quality for low pressure boilers.

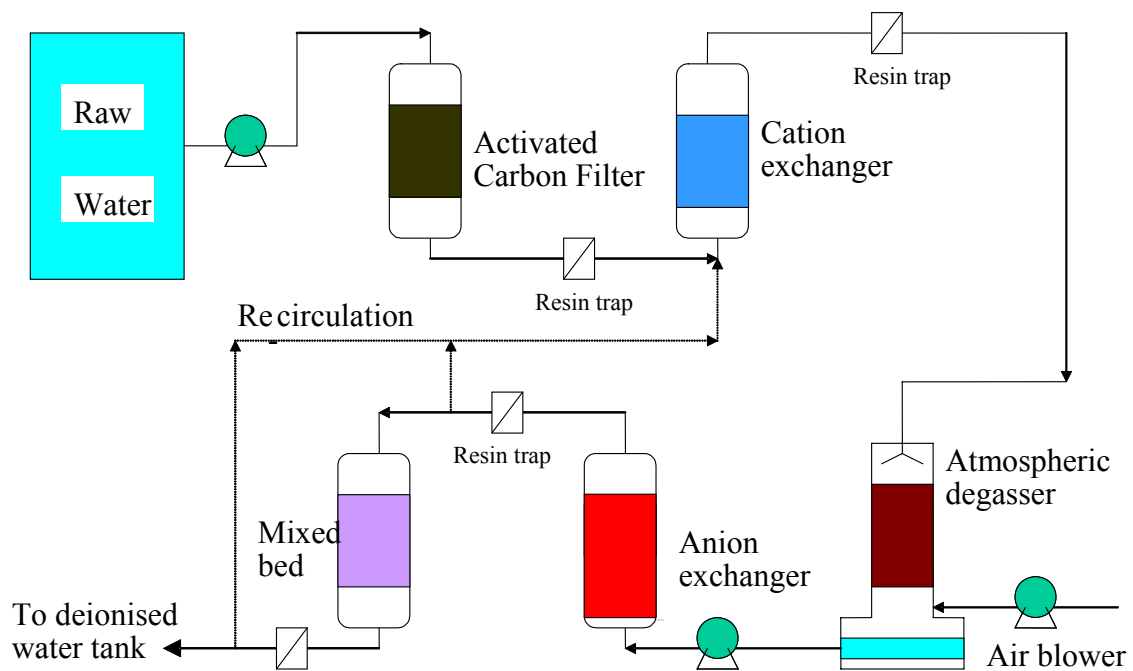
For higher pressure boiler operating in excess of 60bar, a two bed cation-anion exchange system will not produce water of sufficiently high purity for use as boiler makeup. A well designed counter-current regenerated plant should produce water with a conductivity <2.0 $\mu$ S/cm at the anion exchanger outlet. However, the high purity requirement for boiler makeup is for water with a conductivity <0.2 $\mu$ S/cm. In order to achieve this high degree of purity a mixed bed is normally used to polish the water from the two bed stream. A properly functioning polishing mixed bed should produce water of conductivity <0.1 $\mu$ S/cm (at 25°C reference temperature). The conductivity of absolutely pure water is 0.054 $\mu$ S/cm. Alternatively, a cation exchanger may be used instead of a mixed bed to polish water from a two bed stream to produce a deionised water of similar quality.

The various combinations of ion exchange systems shown in Figure 7.1 represent the majority of system designs currently used to produce makeup water for fossil fuel power plants. Depending on raw water composition, product water quality and chemical regenerant utilisation requirements, variations from these standard designs are

possible. A typical ion exchange plant design for a modern power plant is schematically shown in Figure 7.2.



**Figure 7.1 : Makeup Water Treatment Plants (Courtesy of BEI)**



**Figure 7.2 : Typical Modern Makeup Water Treatment Plant  
(Courtesy of E.ON UK)**

Ion exchange technology for deionised water production in power plants is now essentially a mature technology. The most important developments in ion exchange technology in the last decade have been primarily related to improvements in process design to increase overall performance and reduce chemical regenerant requirements and wastewater volumes. The most notable developments in ion exchange technology are outlined below.

### **7.1 Countercurrent Packed Bed Technology**

Standard countercurrent technology, utilising block-flow techniques have been in use from the early 1960's. Although packed bed technology was known and used at that time, it was not until the early and mid 1990's that this technology was being aggressively marketed as "new technology" by all major resin suppliers. This was due in part to competition from other emerging technologies and more importantly to accommodate the new interest of users to improving operating efficiencies and in complying with stricter wastewater discharge limits.

In a packed bed system, each ion exchange vessel is almost completely filled with ion exchange resin with only a small freeboard above the resin to allow resin movement and swelling. Depending on the original equipment manufacturer, the packed beds may be operated as downflow service/upflow regeneration or upflow service/downflow regeneration.



## **7.2 Stratified or Layered Beds**

A layered bed of ion exchange resins involves the use of two cation resins or two anion resins in a single vessel. A cation layered bed is generally composed of a weak acid resin and a strong acid while an anion layered bed uses weak base and strong base resins. Layering of the resins is made possible by the density and particle size differences between the two resins. Improved regeneration efficiencies and improved operating capacities can be attained using layered beds. In some plant designs, the two resins are held in two compartments separated by a division plate.

## **7.3 Uniform Particle Size Resins**

Uniform particle size resins now predominates the ion exchange resin marketplace. In contrast to the standard Gaussian particle size distribution of traditional resins, these resins contain only beads that are produced in a very narrow particle size range. The resins are considered to offer better ion exchange kinetics, stronger physical strength and improved separation when used in mixed bed applications. These advantages result in higher regeneration efficiency, increased operating capacities, lower pressure drop and reduced ionic leakage.

## **7.4 Short Cycle Deionisation**

Short cycle deionisation systems employ two shallow beds of cation and anion exchange resins. In order to ensure proper distribution of water and regenerant through these shallow beds, the exchange vessels are fully packed with fine particle sized resin such that no freeboard exists. This fine mesh resin is approximately one quarter of the diameter of normal exchange resins. The use of fine mesh resins in a packed bed design improves ion exchange kinetics and allows more efficient rinsing.

The operation of short cycle deionisation systems is also distinctive from conventional deep bed ion exchange systems. In deep bed systems the resin is operated to achieve around 90% exhaustion before regeneration whereas in short cycle systems the resin is regenerated after less than 20% of its capacity has been used. Depending on the total dissolved solids content of the raw water, the service cycle time can range from 10 to 120 minutes. A deep bed system can last from 6 to 20 hours, depending on design. The regeneration and rinsing stages for short cycle system typically takes 7 to 10 minutes compared to 2 to 4 hour duration for regeneration of a deep bed.

The quality of deionised water produced by a two bed (cation/anion) short cycle system is around  $0.2\mu\text{S}/\text{cm}$ . An additional downstream cation polisher can be employed to achieve water quality better than this value.

Whilst there are many of these short cycle plants in operation worldwide, there has been limited application in the power sector, particularly in the UK.

## **7.5 Shallow Shell Resin Technology**

Shallow shell resin technology employs resin beads with an inert inner core and an outer shell of uniform depth containing the ion exchange functional groups. This results in the resin having very fast ion exchange kinetics, similar to fine mesh resin, but, do not have the high pressure drop observed with fine mesh resin. There are no reported applications in power plant makeup water treatment plants.

## **7.6 Ion Exchange Pretreatment Requirements**

The level of pretreatment for ion exchange plant depends on the source of the raw water supply. For municipal water, which has been previously clarified and filtered, filtration by a sand filters or backwashable cartridge filters would be sufficient. For small ion exchange plant supplied with municipal water, disposable cartridge filters may be used. For water supplies sourced from river or lake water, which may contain relatively high levels of suspended solids, it will be necessary to use some form of clarification and filtration process to produce a suitably clarified water. It may also be necessary to undertake some form of biocidal dosing, such as chlorination, to control microbiological activity within the plant. However, care must be taken to ensure protection of the resins from degradation from exposure to high levels of oxidising biocides.

Conventional co-current and countercurrent ion exchange beds with backwashing capability can tolerate a small level of suspended solids in the feed water, though their accumulation would lead to channelling and premature exhaustion of the resin. However, in the case of the more modern packed bed systems which cannot be backwashed in situ, the resin beds can rapidly foul if exposed to any suspended solids present in the feed water. To minimise problems caused by suspended solids fouling these packed beds, an external backwash tank is generally supplied with the plant to allow the resins to be backwashed.

If the water supply is derived from borehole, i.e. groundwater, it may be necessary to undertake some form of aeration, clarification and/or filtration, if the water supply contains high levels of iron and manganese which will foul cation resins.

## **7.7 Operational Problems**

Changes in raw water quality can have a significant impact on both the plant performance and deionised water quality. Thus it is important to fully assess any significant seasonal variations in raw water quality prior to the design of any new plant.

Poor plant performance can be the result of several root causes. The potential problems are summarised below:

- Improper regeneration caused by incorrect regeneration flows, injection times, regenerant concentration or poor resin separation in the case of mixed bed systems
- Channelling from either high or low flow rates, fouling by suspended solids or poor backwashing.
- Fouling of cation exchange resin by iron, manganese or aluminium or precipitated calcium sulphate.
- Oil fouling of resins

- Microbiological fouling
- Silica fouling of anion exchange resins.
- Organic fouling of anion resins
- Degradation of resins by oxidising agents such as chlorine or by high temperature.

For many of these fouling problems, the ion exchange resin can be chemically cleaned or treated to return their condition and performance to almost its original prior to the fouling. However, in the case of oxidation or thermal degradation, the deterioration in resin condition is irreversible and resin replacement would be necessary. For maximum reliability of the ion exchange, it is necessary to ensure, as reasonably practicable, that the performance of the plant is monitored and preventative methods are in place to ensure that any fouling or other detrimental condition is identified rapidly and resolved.

## **8 CURRENT STATUS OF CONDENSATE POLISHING**

### **8.1 Application of Condensate Polishing**

At the heart of almost all condensate polishing plants is an ion exchange system, with both anion and cation exchangers. These are always strongly acidic cation exchangers and strongly basic anion exchangers. Anion exchangers have a temperature limit of about 40°C for successful long term operation. Therefore, the condensate polishing plant is located in the coolest part of the condensate/feedwater system, immediately downstream of the condenser after the condensate extraction pumps.

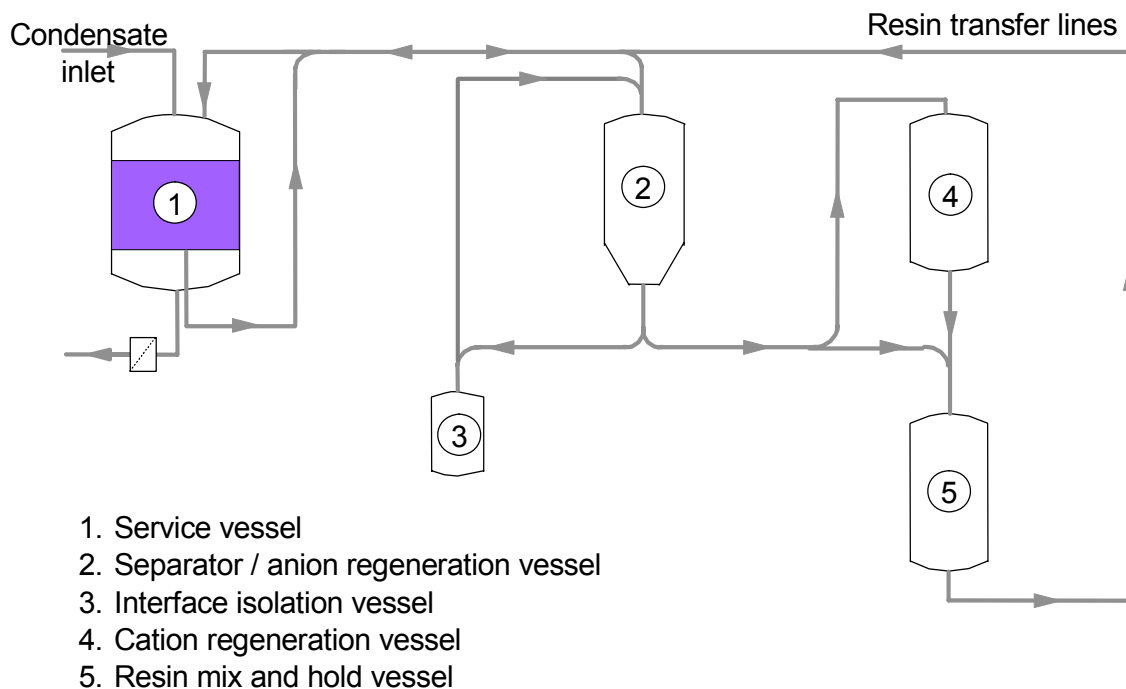
### **8.2 Condensate Polisher Design**

The simplest condensate polishing plant design is a simple mixed bed, regenerated with acid and alkali, so that the cation exchanger operates in the hydrogen ion form and the anion exchanger in the hydroxide ion form. Thus all impurities in the condensate are exchanged for the components of water. Unfortunately, this system also removes the ammonia that has been added to the feedwater to maintain the feedwater, steam and condensate pH. Therefore, ammonia has to be continually added downstream of the CPP to replace that removed by the cation exchanger in the CPP. In the absence of any significant impurity ingress the main ionic load onto the CPP is ammonia. In addition to its ion exchange function the mixed bed can act as an effective filter for particulate species, of which iron oxide debris is the most common. At times of high particulate loading, e.g. return to service after an outage, a mixed bed may be taken out of service because of high pressure drop due to particulate loading rather than ionic exhaustion.

Because ammonia is the main loading onto the mixed bed it is quite common to have a system where each mixed bed contains a larger volume of cation exchanger than anion exchanger to prevent premature exhaustion or too frequent regeneration. A typical condensate polishing plant and its associated regeneration facility, based on a mixed bed system design, is shown in Figure 8.1.

An alternative to a mixed bed with a high cation: anion exchanger ratio is to install a two bed system, with a cation exchange bed ahead of a mixed bed. In this case the cation exchange bed acts as a particulate filter and ammonia removal stage and protects the mixed bed from particulate fouling. The cation exchanger will be regenerated as required and the mixed bed will be regenerated on a much lower frequency. A third type of system is to place a stand alone filter ahead of the mixed bed. Latterly, candle filters which can be coated with a replaceable filter medium, e.g. powdered cellulose fibres, have been used. There have been a number of operational problems with pre-coat candle filters, particularly fouling of the support candles.

Another alternative to the mixed bed has been the use of a three bed system of separate cation exchange, anion exchange and cation exchange. The resins may be in separate vessels or all three resins can be incorporated within a single vessel, with suitable distributors and separators. It has operational flexibility and a simpler regeneration system than the mixed bed.



**Figure 8.1 : Typical Process Diagram for Condensate Polishing Plant (Courtesy of E.ON UK)**

In all cases where deep beds of regenerable ion exchange resins are used it is normal practice to carry out regeneration in an external facility which is common to a number of beds. The resins are transferred between the service vessels and the regeneration system by hydraulic or hydro-pneumatic means.

An alternative to deep bed ion exchange is to use the candle filters to support a coat of finely ground mixed anion and cation exchangers. This has the advantage of combining an effective filter with ion exchange and there is no regeneration as each coating is discharged to waste. However, this system has very limited ion exchange capacity and has limited application. It is not suitable for sea water cooled stations, as the exchange capacity would not be adequate in the event of a condenser leak.

### **8.3 Plant Configuration**

In order to limit their physical size, condensate polishing plant mixed beds operate at high flow rates, typically  $100\text{m}^3\text{m}^{-2}\text{h}^{-1}$  superficial flow rate through the bed. Depending on the degree of protection required and the total condensate flow rate the configuration of plant installed on any one unit may vary. Configurations of 1 x 100%, 2 x 100%, 2 x 50% and 3 x 50% streams are the most common examples found in power plant applications.

The 1 x 100% arrangement gives the lowest level of protection in that when the bed is exhausted there is no cover until a freshly regenerated bed is returned to service. The 2 x 50% format allows 50% cover during regeneration and the 2 x 100% or 3 x 50% formats ensure that there is always 100% condensate polishing available. However, the provision of full availability 100% polishing carries with it a capital cost penalty for the plant.

Depending on the chosen configuration and design, typical capital costs associated with the installation of a condensate polishing plant range from £1.5 – 3.0 million. It is not possible to provide typical operating costs for condensate polishing as these vary widely due to the various operating regimes employed and the level of contaminants present in the condensate which affect polisher operation and regeneration frequency.

#### **8.4 Condensate Polishing Resin Regeneration**

The condensate polishing plant service vessels are designed essentially to optimise the flow through them, with adequate condensate collection and distribution systems. Unlike demineralisation plant mixed beds, regeneration does not take place within the service vessel, but in a separate, purpose designed facility. This is to avoid any chance of regenerants leaking from the regeneration system into the condensate and feedwater and also to be able to design a system that is optimised for regeneration, rather than a compromise of service and regeneration requirements. One regeneration facility is normally provided for all condensate polishing units within a power plant. Therefore, for some of the units the resin transfer lines will be very long.

Demineralised water is normally used in all of the resin transfer, clean-up and regeneration processes in order to minimise contamination of the resins with any impurities that may subsequently be transferred to the polished condensate. Schematic diagrams for each stage of regeneration are shown in Figures 8.2 – 8.7.

##### **8.4.1 Resin Transfer**

The resins are transferred from and returned to the service vessel by hydraulic motive power. The system is designed to remove as much resin as possible from within the service vessel by backwashing and sluicing across the bottom collector nozzle plate to a centre transfer point. Motive water can also be provided from the top of the vessel if required. The resin is transferred to the combined resin separation and anion regeneration vessel. This may take up to an hour, dependent on the distance of the service vessels from the regeneration facility. At the same time the resin left in the interface isolation vessel from the previous regeneration is transferred to the separation vessel.

##### **8.4.2 Resin Separation**

The resin separation vessel is a tall vessel with a cone shaped lower section. The resins are first air scoured by injecting compressed air at the bottom of the vessel. This loosens and releases particulate matter filtered by the resins. The water is then rapidly drained from the bed, taking with it the relatively dense iron oxide particulate matter.

Backwash water is passed upward through the mixed resins, which separate due to both size and density differences between the anion and cation exchangers and washes out very small particulates and resin fines. The anion exchanger is both of lower density and of slightly smaller bead size distribution than the cation exchanger. The anion exchanger forms a layer above the cation exchanger, but it is very rare that a perfect separation is achieved as there is always some mixing of resins at the interface between the two resins. It is important that good resin separation is achieved as this minimises the cross contamination of unseparated resins by the wrong regenerant, which in turn can lead to increased ionic leakage when the bed is returned to service.

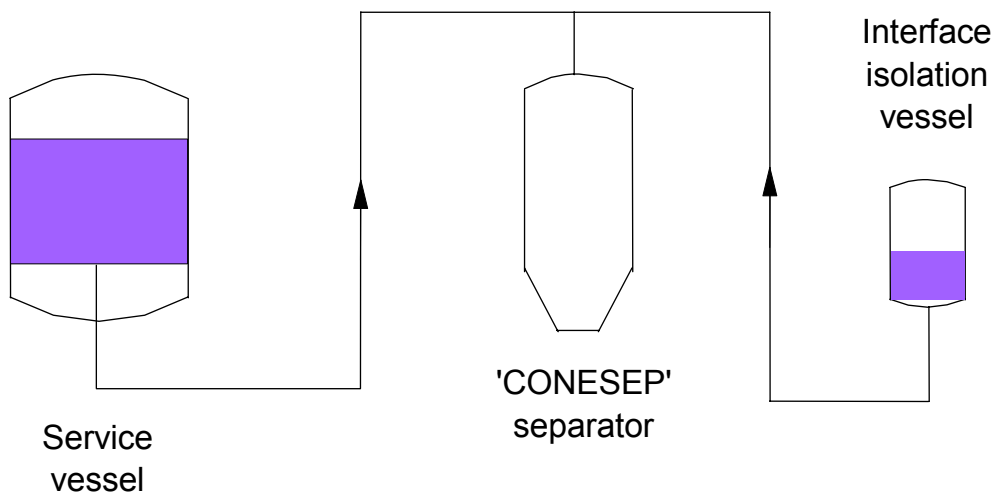
Once the resins are separated the up-flow of water is continued but the lower layer of cation exchanger is extracted, hydraulically, from the bottom of the vessel and is transferred to the cation exchange vessel. A conductivity monitor sampling from the transfer line between the separation vessel and the cation regeneration vessel, detects the change in resin type and initiates a valve changeover which directs the interface resins into the separation isolation vessel. The advantage of the coned vessel bottom is that it increases the backwash flow rate relative to the full width bed and therefore enhances the separation of the two resins.

The conductivity detection of the interface is reinforced by an optical detector based on the differences in reflectivity of the anion and cation exchangers, which will be of different sizes, colour and opacity.

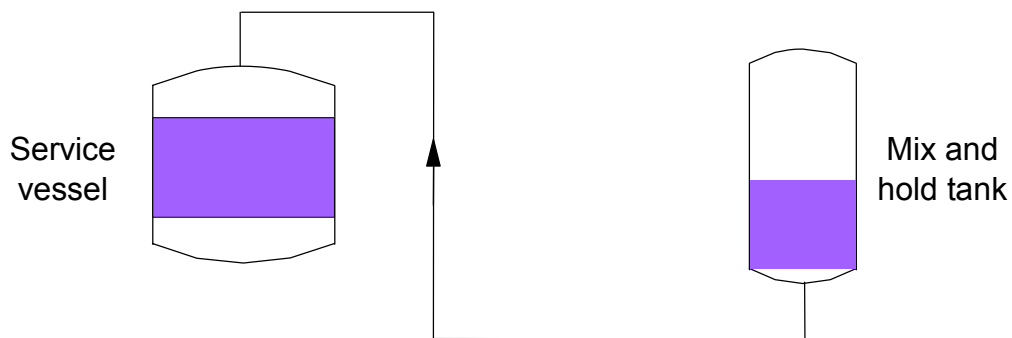
The isolated interface resin remains in the isolation vessel until it is added to the next charge of exhausted mixed resins which arrive for regeneration in the separation vessel.

#### 8.4.3 Resin Regeneration and Remixing

The resin regeneration in the separate anion and cation regeneration vessels takes place normally. The charge of concentrated regenerant, sulphuric acid or sodium hydroxide, is diluted and injected into the appropriate vessel in down-flow mode. Rinsing follows in the same direction. The two resins are then hydraulically transferred to the resin mixing and hold vessel. Compressed air is injected at the base of the vessels to mix the resins. Once mixed, the resins are again rinsed to a low conductivity and then left until the next charge of exhausted resin is transferred to the regeneration station.



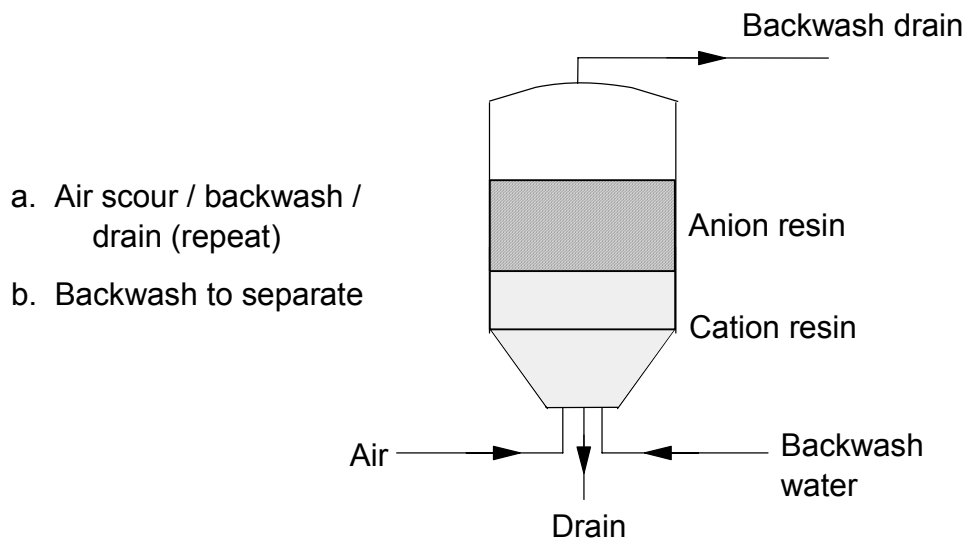
**Figure 8.2 : Transfer to Separation Vessel (Courtesy of E.ON UK)**



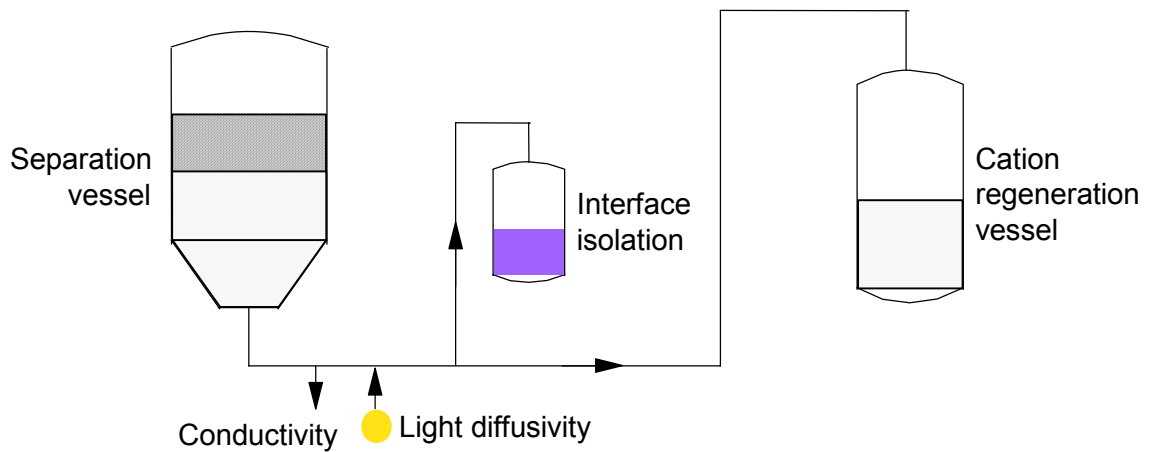
- a. Transfer to service vessel
- b. Remix in service vessel
- c. Rinse recycle in service vessel

**Figure 8.3 : Transfer from hold tank to Service Vessel (Courtesy of E.ON UK)**

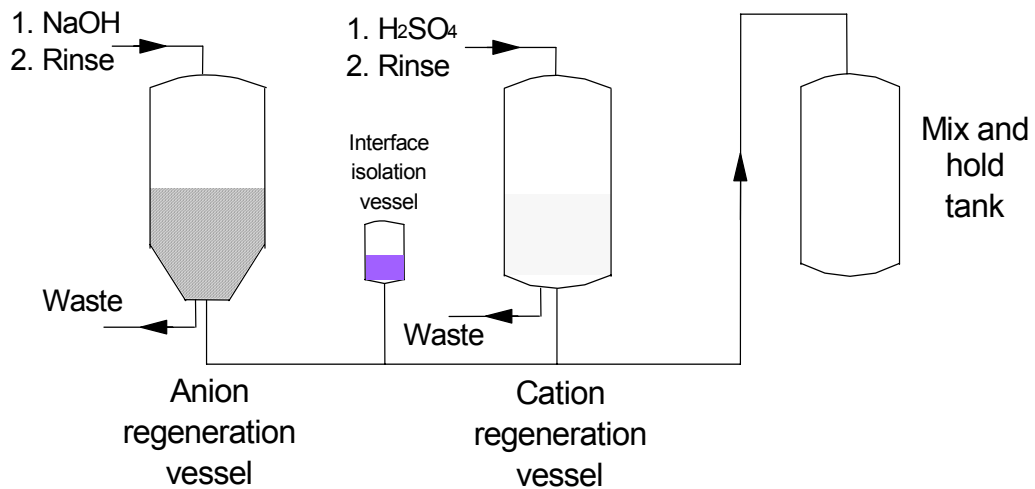




**Figure 8.4 : Resin Clean-up and Separation  
 (Courtesy of E.ON UK)**

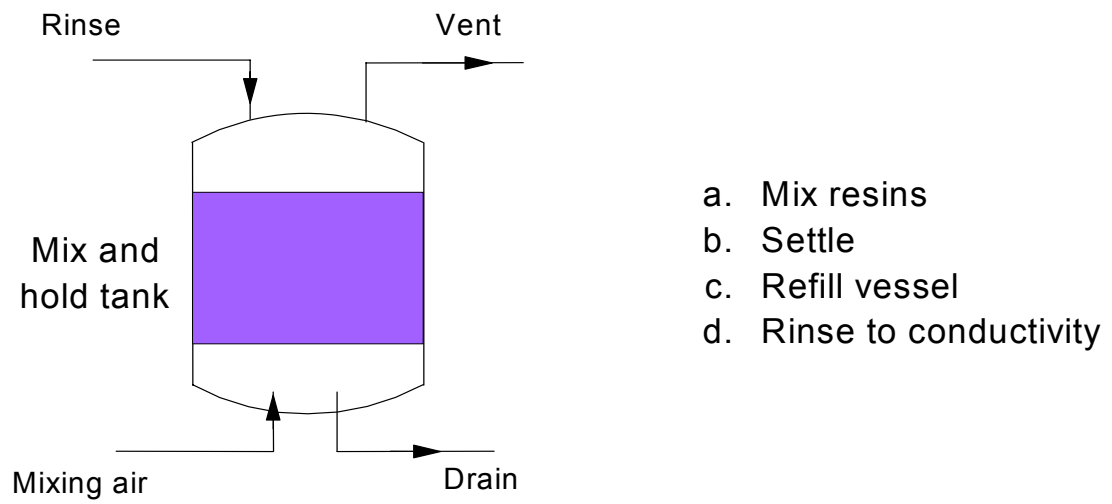


**Figure 8.5 : Resin Transfer and Interface Isolation  
(Courtesy of E.ON UK)**



- a. Anion exchanger regeneration and rinse
- b. Cation exchanger regeneration and rinse
- c. 2nd backwash of anion exchanger
- d. Isolate newly separated cation in anion
- e. Transfer regenerated resins to mix tank

**Figure 8.6 : Anion and Cation Exchanger Regeneration  
(Courtesy of E.ON UK)**



**Figure 8.7 : Mixing and Rinsing – Mix and Hold Tank  
(Courtesy of E.ON UK)**

## **9 REVERSE OSMOSIS TECHNOLOGIES FOR DEIONISED WATER PRODUCTION**

In the last decade, worldwide, there has been a substantial growth in the application of reverse osmosis (RO) membrane technology within the power industry. In contrast, within the UK, the assimilation of this new technology to produce process water for fossil fuel plants has been slow and conventional established treatment processes such as ion exchange remain the preferred option. This apparent reticence to adopt membrane technology is partly due to the conservative nature of the power industry to new technology and in part to the reluctance to invest in new plant and technology unless there is an overwhelming economic driver to justify such investment.

Utilisation of membrane water treatment technology for makeup water treatment can arise in several ways:

- Specification of new makeup water treatment systems
- Expansion of existing makeup water treatment systems
- Refurbishment of existing makeup water treatment systems

Within the UK in the last few years, RO membrane technology has been adopted by several large coal-fired power plants.

### **9.1 Reverse Osmosis System Configuration**

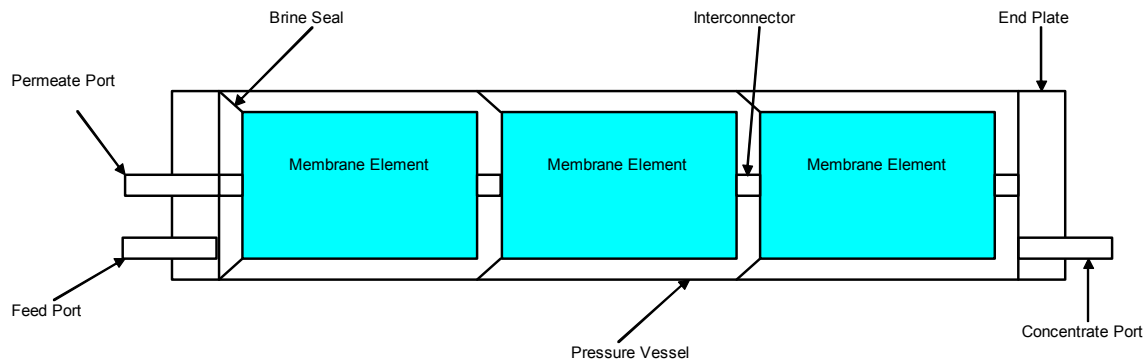
There are several flow configurations for reverse osmosis systems and factors such as raw water composition, final permeate quality and quantity will determine the optimal RO system design. A major influence on system design is the level of recovery required, i.e. the percentage of the feed stream that is recovered as final permeate. Several techniques can be employed to enhance recovery rates and increase system performance. Techniques such as the use of concentrate staging and concentrate recirculation can increase recovery rates. Permeate staging can be used to attain ultrapure standards of separation. Permeate throttling and interstage boosting is used to manipulate the flow distribution between stages.

Most large RO systems tend to be based on the spiral wound membrane design. This particular membrane design tends to be favoured by many RO system manufacturers as it offers a large membrane surface area in a small volume. This compactness leads to cost reductions in terms of pressure vessel sizes and associated pipework. The low pressure drops exhibited by these membranes also provide benefits in terms of reduced energy and pumping requirements. A typical RO system consists of the following basic components:

- Feed water supply unit
- Pretreatment system
- High pressure pumping unit
- Membrane element assembly unit
- Instrumentation and control system
- Permeate treatment and storage unit
- Cleaning unit

The membrane assembly unit (RO module) consists of a rack supporting the pressure vessels, interconnecting piping, and feed, permeate and concentrate manifolds. Membrane elements are installed in the pressure vessels. The pressure vessel has permeate ports on each end, located in centre of the end plate. Feed and concentrate ports are located on the opposite ends of the vessel. Each pressure vessel may contain from one to seven membrane elements connected in series.

As shown in Figure 9.1, the permeate tube of the first and the last element is connected to the end plates of the pressure vessel. Permeate tubes of elements in the pressure vessel are connected to each other using interconnectors. On one side of each membrane element there is a brine seal, which closes the passage between outside rim of the element and inside wall of the pressure vessel. This seal prevents feed water from bypassing the membrane module, and forces it to flow through the feed channels of the element.

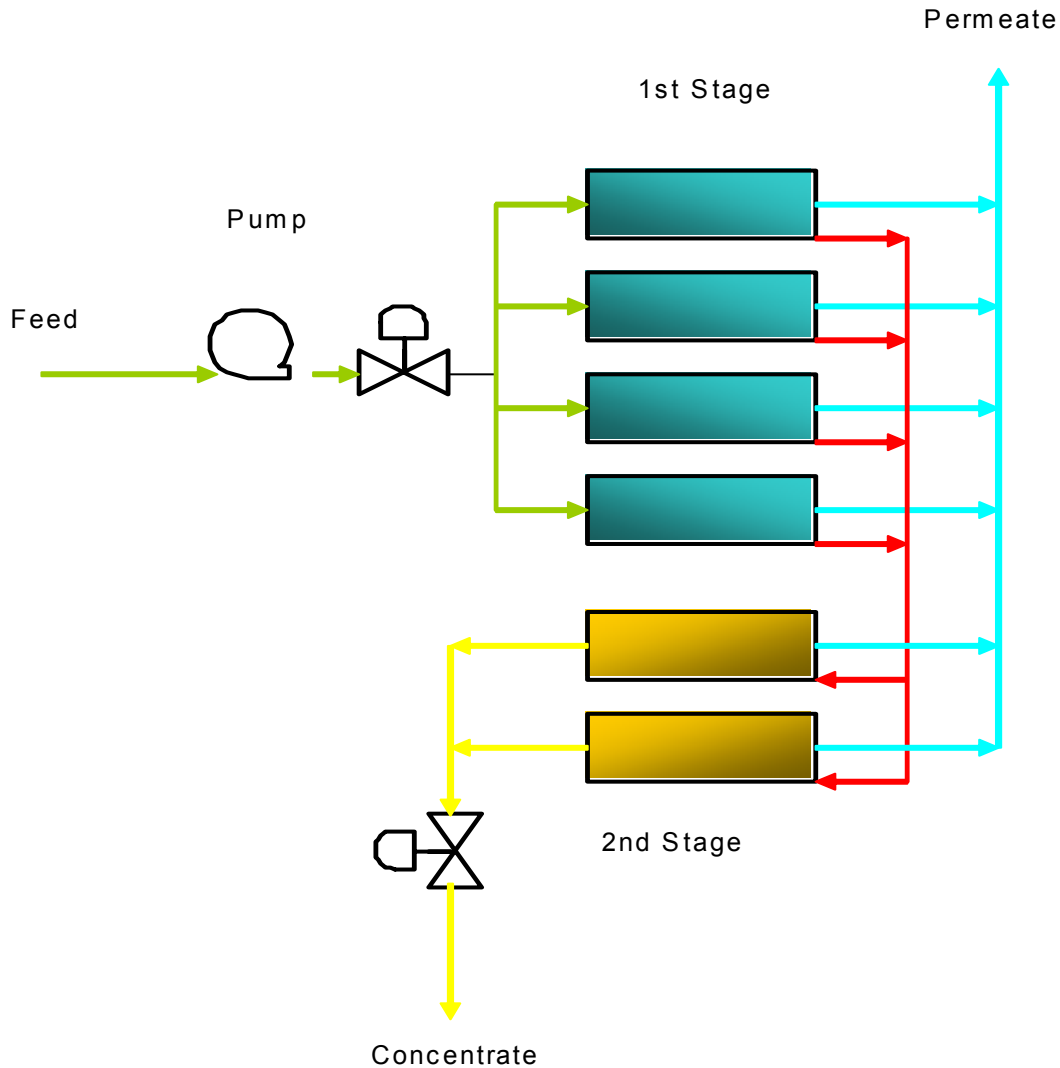


**Figure 9.1 : Pressure vessel showing membrane elements  
(Courtesy of E.ON UK)**

As feed water flows through each subsequent membrane element, part of the feed volume is removed as permeate. The salt concentration of the remaining feed water increases along the pressure vessel. Permeate tubes conduct the permeate from all connected elements. The collected permeate has the lowest salinity at the feed end of the pressure vessel, and increases gradually in the direction of the concentrate flow.

An RO system is divided into groups of pressure vessels, called concentrate stages. In each stage pressure vessels are connected in parallel, with respect to the direction of the feed/concentrate flow. The number of pressure vessels in each subsequent stage decreases in the direction of the feed flow, usually in the ratio of 2:1, as shown in Figure 9.2.

The decreasing number of parallel pressure vessels from stage to stage compensates for the decreasing volume of feed flow, which is continuously being partially converted to permeate. The permeate of all pressure vessels in each stage, is combined together into a common permeate manifold.



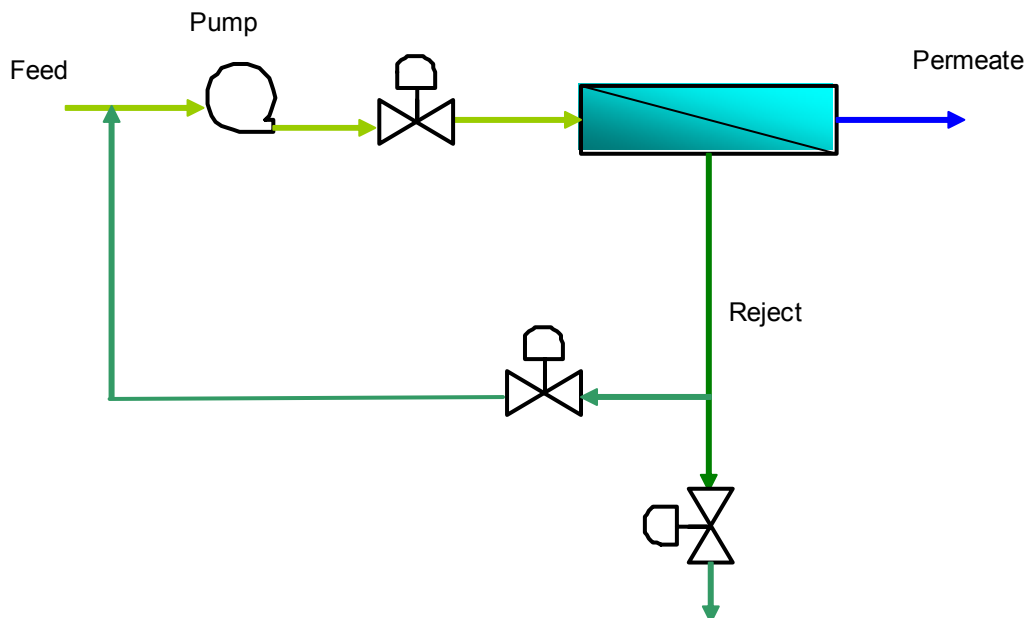
**Figure 9.2 : Flow diagram of a two stage RO system  
(Courtesy of E.ON UK)**

The objective of the taper configuration of pressure vessels is to maintain a similar feed/concentrate flow rate per vessel through the length of the system and to maintain feed/concentrate flow within the limits specified for a given type of membrane element. Very high flow through a pressure vessel will result in a high pressure drop and possible structural damage of the element. Very low flow will not provide sufficient turbulence, and may result in excessive salt concentration at the membrane surface. For a given RO unit, the number of concentrate stages will depend on the permeate recovery ratio and the number of membrane elements per pressure vessel. In order to avoid excessive concentration polarisation at the membrane surface, the recovery rate per individual membrane element should not exceed 18%. It is common engineering practice to design brackish RO systems so that the average recovery rate per 40 inch long membrane element will be about 9%. Accordingly, the number of concentrate stages for an RO unit having 6 elements per pressure vessel would be two for recovery rates over

60%, and three for recovery rates over 75%. With pressure vessels containing seven elements, a two stage configuration would be sufficient for recovery rates up to 85%.

## 8.2 Concentrate Recirculation

The simplest membrane element assembly consists of one pressure vessel, containing one membrane element (Figure 8.3). Such a configuration, used in a very small systems, can operate at a limited permeate recovery ratio, usually about 15%. In order to increase the overall system recovery ratio and still maintain an acceptable concentrate flow, part of the concentrate stream is returned to the suction of the high pressure pump. The concentrate recycling configuration, (Figure 9.3), is used mainly in a very small RO units. An advantage of such a design is the compact size of the RO unit. The disadvantage of concentrate recirculation design is related to the need for a larger feed pump to handle higher feed flow. Accordingly, the power consumption is relatively higher than that required in a multistage configuration. Due to blending of the feed with the concentrate stream, the average feed salinity is increased. Therefore, both the feed pressure and the permeate salinity are higher as well.



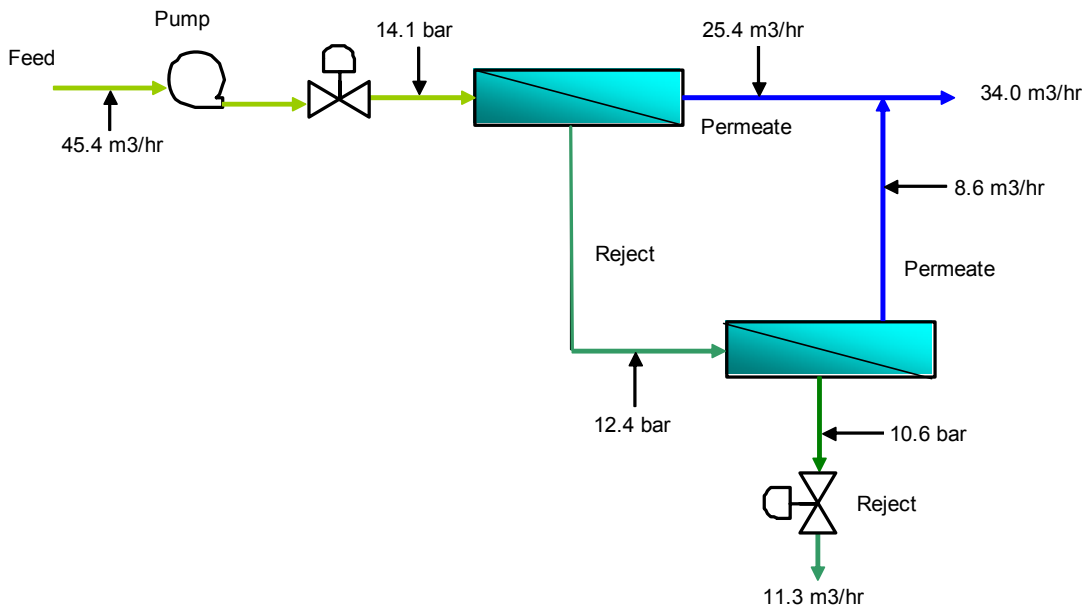
**Figure 9.3 : Flow Diagram of a single stage RO module with concentrate recirculation  
(Courtesy of E.ON UK)**

## 9.3 Concentrate Staging

A commercial RO unit usually consists of single pump and a multistage array of pressure vessels. A simplified block diagram of a two stage RO unit is shown in Figure 9.4.

The concentrate from the first stage becomes the feed to the second stage; this is what is meant by the term "concentrate staging". The flows and pressures in the multistage unit are controlled with the feed and concentrate valves. The feed valve, after the high

pressure pump, controls feed flow to the unit. The concentrate valve, at the outlet of RO block, controls the feed pressure.

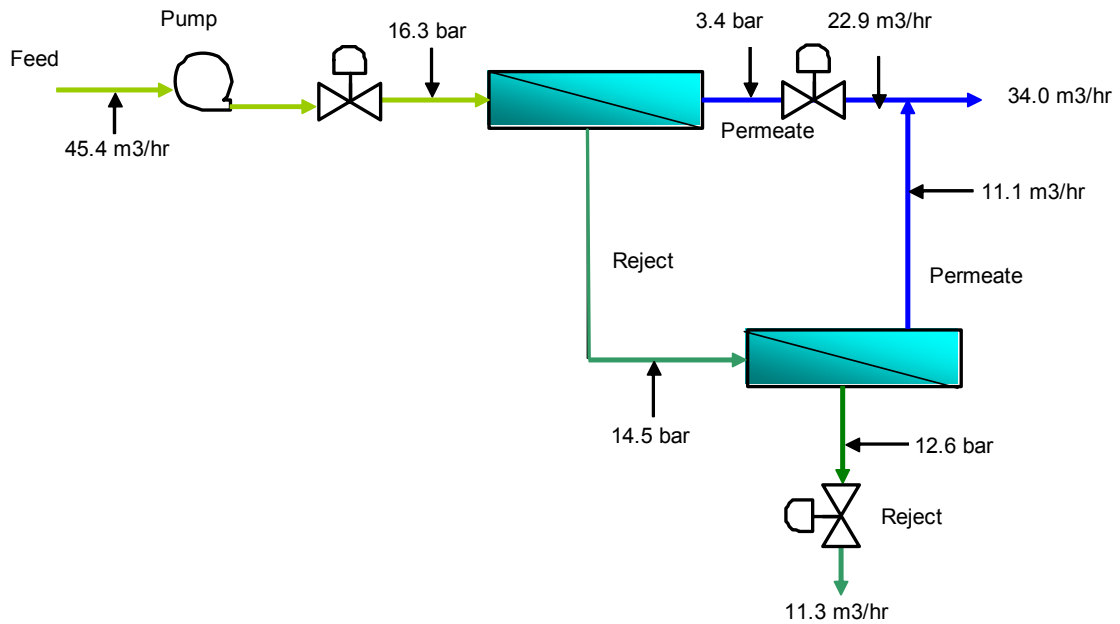


**Figure 9.4 : Flow diagram of a two stage RO system  
(Courtesy of E.ON UK)**

#### 9.4 Flow Distribution

In some cases it is necessary to equilibrate permeate flow between stages, i.e. decrease permeate flow from the first stage and increase permeate flow from the last stage. This can be accomplished in one of two design configurations. One solution is to install a valve on the permeate line from the first stage, as shown (Figure 9.5). By throttling this valve, permeate back pressure will increase, reducing net driving pressure and reducing permeate flux from the first stage. The differential permeate flux is produced from the second stage by operating the RO unit at a higher feed pressure.

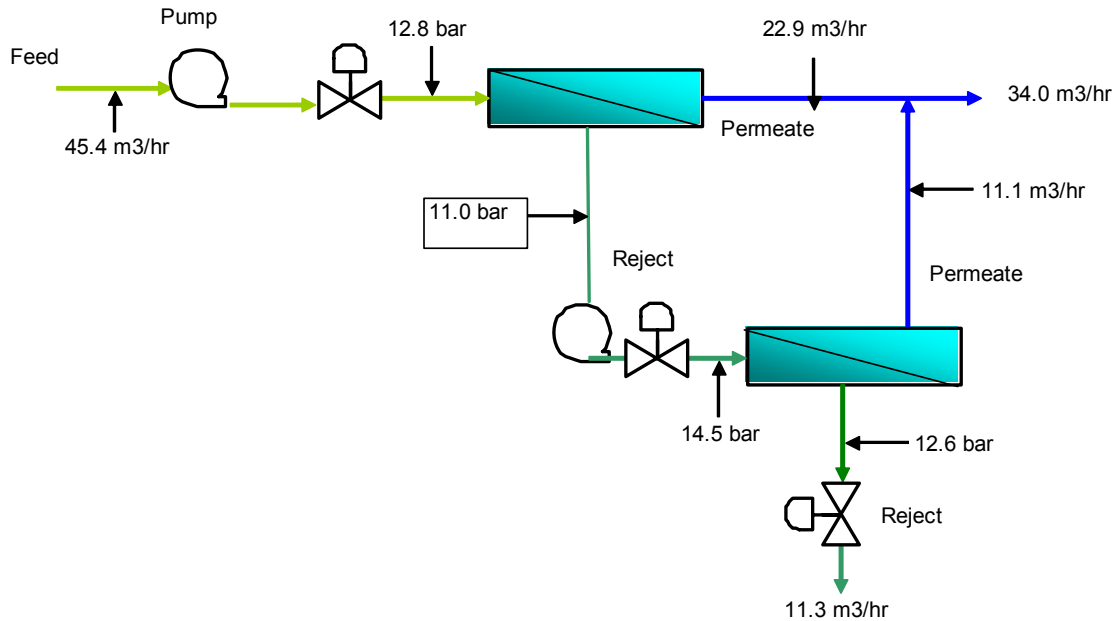




**Figure 9.5 : Flow diagram of a two stage RO system with permeate throttling (Courtesy of E.ON UK)**

The other option is to install a booster pump on the concentrate line between the first and the second stage (Figure 9.6). The booster pump will increase feed pressure to the second stage resulting in higher permeate flow. The advantage of the permeate throttling design is simplicity of the RO unit and low capital cost. However, this design results in additional power losses due to permeate throttling and higher power consumption. The interstage pump design requires modification of the interstage manifold and an additional pumping unit.

The investment cost is higher than in the first design, but the power consumption is lower.



**Figure 9.6 : Flow diagram of a two stage RO system with interstage pump (Courtesy of E.ON UK)**

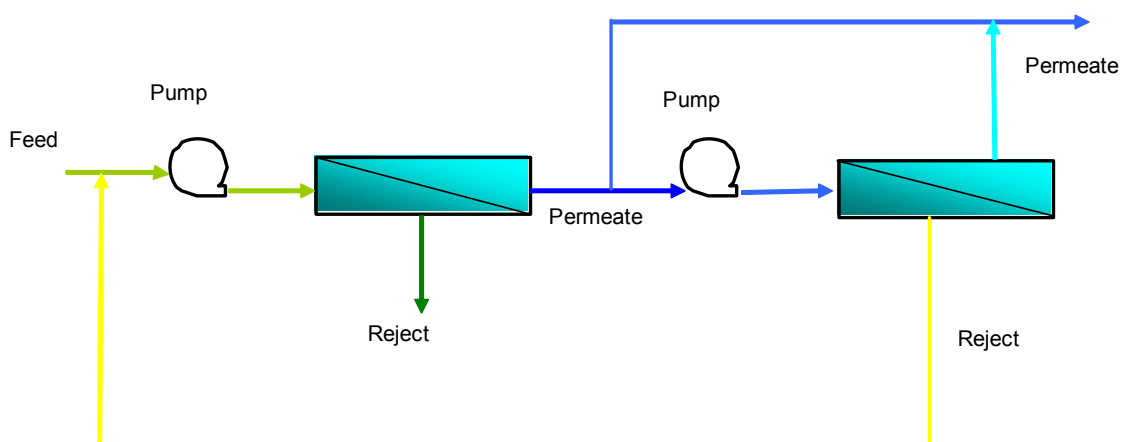
## 9.5 Permeate Staging

For some applications, the single pass RO system may not be capable of producing permeate water of a required salinity. Such conditions are encountered in two types of RO applications:

- Seawater RO systems, commonly referred to as desalination RO, which operate on a very high salinity feedwater, at high recovery ratio and/or at high feed water temperature.
- Brackish RO applications which require very low salinity permeate such supply of makeup water for high pressure boilers.

To achieve an additional reduction in permeate salinity, the permeate water produced in the first pass is desalted again in a second RO system. This configuration is called a two pass design, or "permeate staging". Depending on quality requirements, all or part of the first pass permeate volume is desalted again in the second pass system. The system configuration is known as a complete or partial two pass system depending on whether all of the permeate is fed to the second pass or not.

The first pass permeate is a very clean water. It contains relatively low concentrations of dissolved salts and no suspended solids; therefore, it does not require any pretreatment. The second pass system can operate at a relatively high average permeate flux and high recovery rate. Typically, for the second pass RO unit the recovery rate is of the order of 85 - 90%. In a two pass system the permeate from the first pass flows through a storage tank or is fed directly to the suction of the second pass high pressure pump. There are number of possible configuration of the two pass RO units. One configuration, which is a partial two pass system, (Figure 9.7), splits the permeate from the first pass into two streams.



**Figure 9.7 : Flow diagram of a partial two pass system  
(Courtesy of E.ON UK)**

Part of the permeate stream is processed by the second pass unit, and is then combined with the unprocessed part of the permeate from the first pass. Provided that the partial second pass system can produce the required permeate quality, this configuration results in smaller capital and operating costs, as well as higher combined permeate recovery rate (utilisation of the feed water), compared to a complete two pass system.

It is a common procedure in a two pass systems to return concentrate from the second pass unit to the suction of the high pressure pump of the first pass unit. The dissolved salts concentration in the concentrate from the second pass is usually lower the concentration of the feed to the first pass unit. Therefore, blending feed water with the second pass concentrate reduces slightly the salinity of the feed, and increases the overall utilization of the feed water.

## **9.6 Pretreatment Requirements for RO Systems**

Pretreatment is the key to successful long term RO performance and its importance in system design should not be underestimated. The purpose of pre-treatment is to guard against feed water upsets, remove suspended and colloidal material, prevent membrane scaling resulting from precipitation of sparingly soluble salts and to prevent biological growth.

### **9.6.1 Causes of Scaling and Fouling**

Membrane surfaces can be fouled with colloidal materials, organic matter, metal oxides or hydroxides, biological growth and precipitated salts from the concentrated reject water. Colloidal materials are usually very fine clay particles; organics can be hydrocarbon oils, grease, naturally occurring humic and fulvic acid and tannins. Metal oxides and hydroxides are generally formed from iron, manganese and aluminium species present in the feed water. The presence of suspended solids in the water, such as mud or silt, tends to cause gross plugging of the membrane elements rather than fouling of the membrane surfaces. Mineral scales consists of calcium carbonate, calcium sulphate, calcium fluoride, barium sulphate, strontium sulphate and silica

### **9.6.2 Pretreatment Techniques**

The requirements for removal of colloidal or suspended solids are determined by the determination of the Silt Density Index (SDI) of the feed water. Membrane manufacturers generally specify the SDI required for their membranes which is typically a maximum value of 5. Techniques are available for achieving the required SDI through the use of multimedia filters alone or in conjunction with coagulants with or without a clarification system. As a minimum, 5 – 10 micron cartridge filters can be used prior to the pumps to remove large particles and protect the close tolerance pumps and RO membrane elements. The use of microfiltration membrane systems is increasingly being used to provide protection to downstream RO systems.

Calcium carbonate scale prevention is required on most RO systems. Acidification of the fed water is the most common technique used to convert carbonates to carbon dioxide and to achieve a negative Langelier Saturation Index (LSI) for the feed water.

The LSI is a theoretical measure of the scaling propensity of water based on the calcium hardness, alkalinity, total dissolved salts, temperature and pH of the water; a negative value indicates a non-scale forming water. The need for acidification can be reduced or eliminated by a softening process to reduce calcium hardness. The practice of adding organic polymeric antiscalants is commonly applied to retard precipitation. Scaling caused by other sparingly soluble salts need to be considered as well. Generally, the addition of antiscalant additives or reducing the RO system recovery rate will resolve such issues. Guidelines to control these various scaling species are available from the membrane manufacturers.

Treatment for biological activity may be necessary, depending on the feed water source. It is usually required for fresh surface waters and sea or estuarine water. An oxidising biocide based on chlorine, e.g. sodium hypochlorite or chlorine dioxide, is used to control microbiological fouling. The efficacy of chlorination will be affected by water pH, dosage level and contact time. Thin film composite polyamide membranes cannot tolerate chlorine and the feed water must be dechlorinated before it enters the RO system. Dechlorination is undertaken as close to the membranes as possible by injection of a sodium bisulphite solution.

## **9.7 Factors and Operational Issues Affecting RO Membrane Performance**

### **9.7.1 Recovery Rate**

The recovery rate is commonly used to define the percentage of the feed water that is converted to permeate. At 75% conversion, 100m<sup>3</sup>/hr of feed water is converted to 75m<sup>3</sup>/hr of permeate with 25m<sup>3</sup>/hr of concentrated reject water being produced. The reject stream will contain most of the dissolved salts from the feed water; a small percentage of salts, mainly comprising of sodium chloride, pass into the permeate. This process is known as salt passage. Thus, in this example, the reject will be approximately four times more concentrated in salts than the feed. To conserve energy, it is desirable to operate at a high recovery rate as possible to minimise the size and capital costs of upstream equipment, e.g. pre-treatment equipment and pumps.

Excessively high recovery rates can create high concentration of salts in the reject water which will reduce the permeate flow due to the water having a higher osmotic pressure. Similarly, salt passage will increase, causing poorer quality permeate. There is also a risk with high recovery rates of fouling or scaling occurring from precipitation of sparingly soluble salts from the concentrated reject water.

### **9.7.2 Temperature**

Temperature changes affect both osmotic pressure and the water flux which is the rate of permeate transported per unit of membrane area. Increasing temperature increases the osmotic pressure. The water flux is also directly proportional to temperature. As a rule of thumb, the membrane capacity or water flux increase by about 3% per degree Celsius. The implications of this membrane characteristic is that at higher feed water higher temperatures, higher volumes of permeate can be produced. However, this membrane property presents serious consequences to RO systems operating on surface water sources which experience large seasonal variations in temperature as lower winter temperatures will cause a significant reduction in permeate production.

Thus, the design capacity of a RO system must always be based on the minimum feed water temperature.

### 9.7.3 Pressure

For a given set of feed conditions, increasing pressure results in increased water flow per unit of membrane area, i.e. increased water flux occurs. The transport of salts across the membrane, salt passage, is not affected by pressure. Thus, the increased water flow that occurs with increasing pressure will dilute the salt passing through the membrane, resulting in better quality permeate.

### 9.7.4 Membrane Compaction

The water transport or flux through a clean membrane can decrease with time as a result of membrane compaction. Compaction is caused by creep deformation of the polymeric membranes over time and is dependent on the membrane material, the applied pressure and temperature. As temperature and pressure increase, the tendency to creep is greater. This effect tightens the membranes rejection layer and reduces water transport.

### 9.7.5 Concentration Polarisation

Concentration polarisation results from the build-up of a boundary layer of more highly concentrated solute on the membrane surface than in the bulk liquid. This occurs because water permeation at the membrane surface leaves the more concentrated solute layer which must diffuse back into the bulk liquid. Due to the higher flux rates, spiral membranes have a greater tendency towards concentration polarisation than hollow fibre membranes. Concentration polarisation increases the osmotic pressure at the membrane surface causing a reduction in water flux and an increase in salt transport across the membrane. If the concentration of sparingly soluble salts in the boundary layer exceeds their solubility limits, precipitation or scaling will occur on the membrane surface.

## 9.8 Production of Deionised Water using Reverse Osmosis

Reverse osmosis (RO) systems can be used to substantially reduce the raw water ionic load to produce a high quality permeate stream. RO system operating on treated river water, municipal or groundwater can be expected to achieve recovery rates of between 75 to 95%, depending on water chemical composition and system design. The RO stage of treatment will also effectively remove dissolved naturally occurring organic matter, such as humic and fulvic acids, as well colloidal silica. These substances are difficult to remove by ion exchange and often they are the source of fouling of ion exchange resins, resulting in lower capacity and poor quality water. RO systems are extremely effective in removing these substances.

Due to the salt passage effects, RO membrane technology cannot produce the high purity water necessary for use in high pressure boilers of fossil fuel plant. At best, RO membranes can remove up to 99% of ionic impurities from the raw feed water using either single or double pass reverse osmosis systems, depending on the dissolved solids content of the feed water. Thus, RO treatment can be considered as a primary

“roughing” stage for the production of deionised water. The quality of the permeate produced will ultimately depend on the chemical composition of the feed and the various design operating parameters of the installed RO system.

It is important to note that dissolved carbon dioxide and oxygen is not normally removed by conventional RO systems. Decarbonation treatment of the RO permeate using an atmospheric degasser will remove any dissolved carbon dioxide present. Alternatively, increasing the permeate pH to alkaline conditions by addition of sodium hydroxide followed by further treatment by another RO stage can effect carbon dioxide removal. In the later option the carbon dioxide exists as the ionic bicarbonate species which RO membranes effectively reject.

To attain the required purity of deionised water necessary for use in power plant applications, the RO permeate must be undergo a further purification or polishing stage. It is common to utilise ion exchange technology in the form of mixed beds to achieve this objective. However, increasingly, continuous electrodeionisation (CEDI) systems are being used as an alternative polishing option. These CEDI systems are well suited for this particular application as the RO permeate quality generally meets with the strict feed water quality requirement of CEDI systems (Table 9.1).

Parameter	Operating Limits
Feedwater Conductivity Equivalent (FCE)	< 40 $\mu$ S/cm
Temperature	5 – 45 °C
Pressure	1.4 – 7 bar
Free Chlorine	< 0.02 mg/litre
Iron, Manganese, Sulphide	< 0.01 mg/litre
pH	4 - 10
Hardness	< 1 mg/litre as CaCO <sub>3</sub>
Silica	< 1 mg/litre
Total Organic Carbon	< 0.5 mg/litre as C

**Table 9.1 : Typical CEDI Feed Water Specification**

The all membrane combination of RO and CEDI to produce high purity deionised water offers distinct advantages in that the whole process does not rely upon the storage and handling of bulk chemicals that a conventional ion exchange system requires. Additionally, there are no large volumes of waste chemical regenerants to be neutralised and discharged.

Increasingly, RO systems are being used in desalination processes to produce fresh water from high salinity waters such as seawater and other brackish estuarine sources. In seawater reverse osmosis, higher pressures, typically 30 – 75bar, are necessary to overcome the high osmotic pressure of these waters. RO desalination systems operate at recovery rates of 30 to 60%, depending on feed water concentration, allowable maximum reject concentration, and the maximum feed pressure the membranes can tolerate. The permeate from such systems can used as process water for many applications within a power plant. However, due to its chemical composition, this RO permeate is considerably aggressive to materials commonly used in water distribution

systems such as carbon steel. Therefore, the use of RO permeate does require careful consideration and selection of compatible materials in any process in which it is to be used. To obtain deionised water, it is necessary to feed the desalination RO permeate through a secondary RO system, generally after degassing to remove carbon dioxide, to produce a product water of low total dissolved salts. The permeate from this secondary RO system is then further polished by either an ion exchange mixed bed or a CEDI system to obtain high purity deionised water.

### **9.9 High Efficiency Reverse Osmosis**

High efficiency reverse osmosis (HERO™) is a particular development of conventional reverse osmosis membrane technology that operates with the feed water at the highest pH that can be tolerated by the membranes. Typically, the feed pH is adjusted by sodium hydroxide addition to attain a pH in the range of 10.0 to 10.5. A normal RO system would employ a feed pH of 6.0 - 7.0. It is claimed that by operating at this high pH, microbiological fouling is eliminated and membranes are self cleaning. As the negatively charged surface of normal composite polyamide membranes is enhanced at high pH, it is claimed that particulates, typically having a negative charge, are strongly repelled, thereby reducing the fouling potential. The HERO™ process is also claimed to have excellent rejection of organic species and silica and can operate at recovery rate of 95%.even with brackish water.

Due to the use of high pH, the hardness of the feed must be reduced to less than 0.1mg/litre. Thus, the HERO™ process involves a hardness and alkalinity removal stage which normally consists of weak and strong acid cation exchangers. This is followed by degasification to remove carbon dioxide and then sodium hydroxide addition to raise the pH of the feed prior to the RO stage. The resulting permeate has a pH between 9.3 - 9.8. Polishing of this permeate by either a mixed bed ion exchanger or CEDI is required to achieve deionised water quality.

### **9.10 Low Fouling Membranes**

The best reverse osmosis membrane is one that has a neutrally charged surface to minimise the attachment of charged foulants, can be used with a biocide to control biological fouling and has a high surface area to decrease flux and increase crossflow velocity. Historically, cellulose acetate membranes with its neutral surface charge a resistance to biocidal chlorine up to levels of 1 part per million (ppm) or around 26,000 ppm-hours, exhibited the best fouling resistance for difficult water applications. However, these membranes had pH limitations, higher feed pressure requirements and higher salt passage when compared to the popular negatively charged composite polyamide membranes.

A new generation of low fouling composite polyamides have now been developed and are available for industrial applications. These membranes have the unique advantages of equivalent rejection and feed pressure requirements of the normal composite polyamide membranes and the neutral surface charge of cellulose membranes. However, being a polyamide these low fouling membranes still exhibit a low tolerance to chlorine of approximately 1,000ppm-hours.

Apart from possessing a neutral surface charge, the membranes also exhibit a more hydrophilic nature. The combination of these two characteristics minimises the adsorption of hydrophobic organic foulants, e.g. humic and fulvic acids, onto the membrane surface. Flux degradation due to the build up of foulants such as organics, hydrophobic metal gels, e.g. iron, and charged colloidal materials, is thus minimised. The membranes can operate over a large pH range whilst still maintaining their neutral surface charges.

### **9.11 The Economics of Ion Exchange versus Reverse Osmosis**

The first question that must be addressed in the design of a new or replacement water treatment plant is whether to install a straight ion exchange system (IX), reverse osmosis/mixed bed ion exchange (RO/IX) or reverse osmosis/continuous electrodeionisation system (RO/CEDI). The principal drivers for such a decision will be economic in terms of capital and operating costs, as well as regional requirements for chemical and waste water disposal. In many cases, familiarity with one or other technology is also a factor in the decision process.

The break-even point in total dissolved solids above which it is more economical to use one of these technologies over the others, depends on a number of factors. The economic factors affecting the break-even point include chemicals, resins, membranes, energy, operating labour, maintenance and capital related equipment and plant.

Comparison between these technologies as options for water treatment applications has been the subject of a number of studies. However, the studies have been predominantly undertaken by either resin or membrane manufacturers with the primary objective of defending their particular technology against competition from the other technology. As technical developments in both technology areas continue to be made, such as counter-flow regeneration packed bed systems, narrow particle sized ion exchange resins and high rejection, lower energy membranes, and many of these studies are now outdated and no longer valid. In addition, external factors such as water costs and disposal, power and chemical costs continue to change and are different around the world, further affecting the economics.

Consequently, there is no general consensus on the break-even point, in terms of total dissolved salts, where it is more economical to use IX alone rather than RO/IX or RO/CEDI. However, the break-even figure is believed to be in the range of 200 - 400mg/litre as CaCO<sub>3</sub>. The figure for the higher end of this range is greater than earlier studies and reflects the developments and improvements in efficiency of ion exchange through the application of counter-current packed bed systems. It is also clear that at high total dissolved salt levels of greater than 1000mg/litre as CaCO<sub>3</sub>, an RO option is the most favourable.

In the medium range of 400 – 1000mg/litre of total dissolved salts, the choice of whether to adopt ion exchange or reverse osmosis technology is not clear cut. The final decision on which technology is best will depend on the individual power plant's raw water source and chemical composition, the required water quality and quantity and any environmental constraints. For waters of high alkalinity, ion exchange is likely to be the preferred option as is the case where low residual silica in the deionised water is



required. In contrast, where raw waters contain colloidal silica or there is a requirement to achieve deionised water with low organic content then reverse osmosis would be the ideal candidate option.

The foregoing discussion has centred exclusively around the total dissolved salt content of the raw water and the ability of both ion exchange and reverse osmosis technology to effectively treat such waters in the most economical manner. However, cognisance must also be taken of the costs of pretreatment requirements for each technology and this will depend on the quality of the raw water being used. Similarly, particular constituents of the raw water i.e. dissolved organic matter and colloidal silica and the deionised water quality requirements may define the best technology to be used irrespective of the total dissolved salts content.

Chemical costs for ion exchange plant and energy costs (electrical power) for reverse osmosis are the most important operating expenses. Although capital costs have a significant effect on the total cost of deionised water production for all options, the operating costs are generally recognised as representing the major portion at 70–80% of the total costs. Additionally, more expensive water sources such as municipal sources will have a higher impact on reverse osmosis costs unless the reject concentrate from the plant is used efficiently elsewhere on site.

The capital costs associated with an ion exchange plant can vary widely due to differences in plant design and the characteristics of the raw water to be treated. Indicative capital costs for a standard ion exchange plant based on 2 x 100% countercurrent streams with sand filter pre-treatment and a production capacity of 100m<sup>3</sup>/hour are of the order of £1 – 1.5 million. Operating costs, excluding raw water costs, can typically range from £0.05 – 0.15/m<sup>3</sup> of deionised water, depending on regenerant levels employed and bulk chemical costs.

The capital costs of a membrane based plant based on microfiltration pre-treatment, a reverse osmosis plant and polishing ion exchange system with a similar production capability of 100m<sup>3</sup>/hour can range from £1.5 – 2.5 million depending on the design of the plant and fouling nature and chemical composition of the water supply. Associated operating costs, excluding raw water and power, typically range from £0.07 – 0.16/m<sup>3</sup> of deionised water.

## **9.12 Case Studies**

The following is a series of case studies covering both the UK and international fossil fuel power plant highlighting the recent application of reverse osmosis systems for the production of deionised makeup water.

### **9.12.1 Case Study 1**

This UK based 2000MW coal fired power plant utilised river water as its principal source of raw water for its makeup water treatment plant. Historically, the plant has had difficulty in controlling silica levels in the steam to accepted industry standards. As a result silica deposition on the turbine blading occurred, necessitating significant expenditure to clean the blading.

The problem generally occurred during winter, when there have been periods of high rainfall. While the original ion exchange water treatment plant was able to remove reactive silica, the high levels of non-reactive (colloidal) silica passed through the plant into the steam /water circuit of the boilers.

Considerations of the options resulted in the selection of a membrane microfiltration and reverse osmosis plant and for initial treatment and removal of colloidal silica, followed by final treatment by the existing ion exchange plant.

The plant is designed to provide a maximum overall flow of 90m<sup>3</sup>/hr and consists of 4 x 25% immersed microfiltration streams feeding 3 x 33% reverse osmosis streams. Design recovery rates are 80% for the microfiltration plant and 75% in the RO plant. The RO permeate is fed to the original ion exchange plant via a degasser to reduce the carbon dioxide content and corrosiveness of the water.

Sodium hypochlorite is dosed to the raw water upstream of the microfiltration units to reduce the risk of biological fouling. Residual chlorine in the RO feedwater, which is harmful to the RO membranes, is removed by the addition of sodium bisulphite. Sulphuric acid and a proprietary antiscalant are also dosed to the RO feedwater to reduce the risk of chemical precipitation and scaling within the membrane system.

Both the microfiltration and reverse osmosis membranes require periodic chemical regeneration to remove surface foulants. The microfiltration membranes are subject to a weekly maintenance clean with sodium hypochlorite. A recovery clean with a heated sodium hypochlorite or sulphuric acid solution is required only when the pressure differential across the membranes exceeds recommended limits, which has not been necessary as of yet basis.

The final RO product water quality has been well within specification requirements (Table 9.2)

Conductivity	< 50µS/cm
Total Silica	< 1.0mg/l SiO <sub>2</sub>
Non-Reactive Silica	< 0.01mg/l SiO <sub>2</sub>
Total Dissolved Solids	< 30mg/l
Total Suspended Solids	< 0.1mg/l
Total Organic Carbon	< 0.5mg/l C

**Table 9.2 : Permeate Guarantee Quality**

### 9.12.2 Case Study 2

Another UK based 2000MW had, historically, obtained its raw water supply for the makeup water treatment plant by abstraction from an aquifer via boreholes. However, faced with its abstraction licence not being renewed an alternative water source had to be found. The plant already abstracted river water fro cooling water use and it was decided to use this as a source for the makeup water treatment plant.

The raw water is taken from the cooling water system and pretreated by two streams of immersed membrane microfiltration, the filters having a nominal pore size of 0.2µm. Acid and hypochlorite are dosed to the raw water upstream of the filters. Water passing through the CMFs is collected in a filtrate tank and, from there, is pumped to the RO units. Water from the filtrate tank is dosed with a phosphonate based antiscalant and bisulphite to remove any residual chlorine before the RO system.

The RO system consists of two streams, each with two membrane arrays. The first array consists of 10 pressure vessels of membranes, from which the reject water is fed to a second array of 5 pressure vessels. Each pressure vessel contains 6 membranes.

The RO permeate is of much better quality than borehole water, and is fed to the existing demineralisation plant. The result is longer run lengths in the demineralisation section and lower regenerant chemical consumption. The quality of the river water and permeate are shown in Tables 9.3 and 9.4.

Parameter Value	Range
Conductivity	770 – 2400µS/cm
Hardness	350 -860 mg/litre as CaCO <sub>3</sub>
Total Dissolved Solids	480 – 1630mg/litre
Suspended Solids	11 – 80mg/litre
Total Organic Carbon	10 – 20mg/litre as C

**Table 9.3 : River Water Quality**

Parameter Value	Range
Conductivity	< 50µS/cm @ 20 °C
Silica	< 1.0mg/litre
Total Dissolved Solids	< 50mg/litre
Total Organic Carbon	< 0.02mg/litre as C

**Table 9.4 : Guarantee Quality for RO Permeate**

### 9.12.3 Case Study 3

A recently commissioned combined cycle power plant with 1176MW capacity in Portugal had to be designed to utilise the nearby river for all its water requirements including cooling water and feed water to its makeup water treatment plant.

Typically, this river water was polluted both by industrial waste and by domestic sewage. In addition it experienced variable flows during the different times of the year and at high tide conditions it frequently experienced high salinity conditions due to contamination with sea water. During dry periods the water in the area was predominantly sea water. After nearly a year of detailed water sampling and analysis, the seasonal variability of the river water was determined. A summary of chemical composition of the river water is shown in Table 9.5. The deionised makeup water quality is shown in Table 9.6.

Parameter	Minimum	Typical	Maximum
Conductivity $\mu\text{S/cm}$	300	10000	20000
Total Dissolved Solids mg/litre	200	7000	13800
Suspended Solids mg/litre	60 -500		
Sodium mg/litre as Na	19	2127	4236
Potassium mg/litre as K	2	78	153
Calcium mg/litre as Ca	23	98	174
Magnesium mg./litre as Mg	6	259	512
Bicarbonate mg/litre as $\text{HCO}_3$	80	92	105
Chloride mg /litre as Cl	22	3814	7605
Sulphate mg/litre as $\text{SO}_4$	36	559	1081
Total Organic Carbon mg/litre as C	3 – 12		

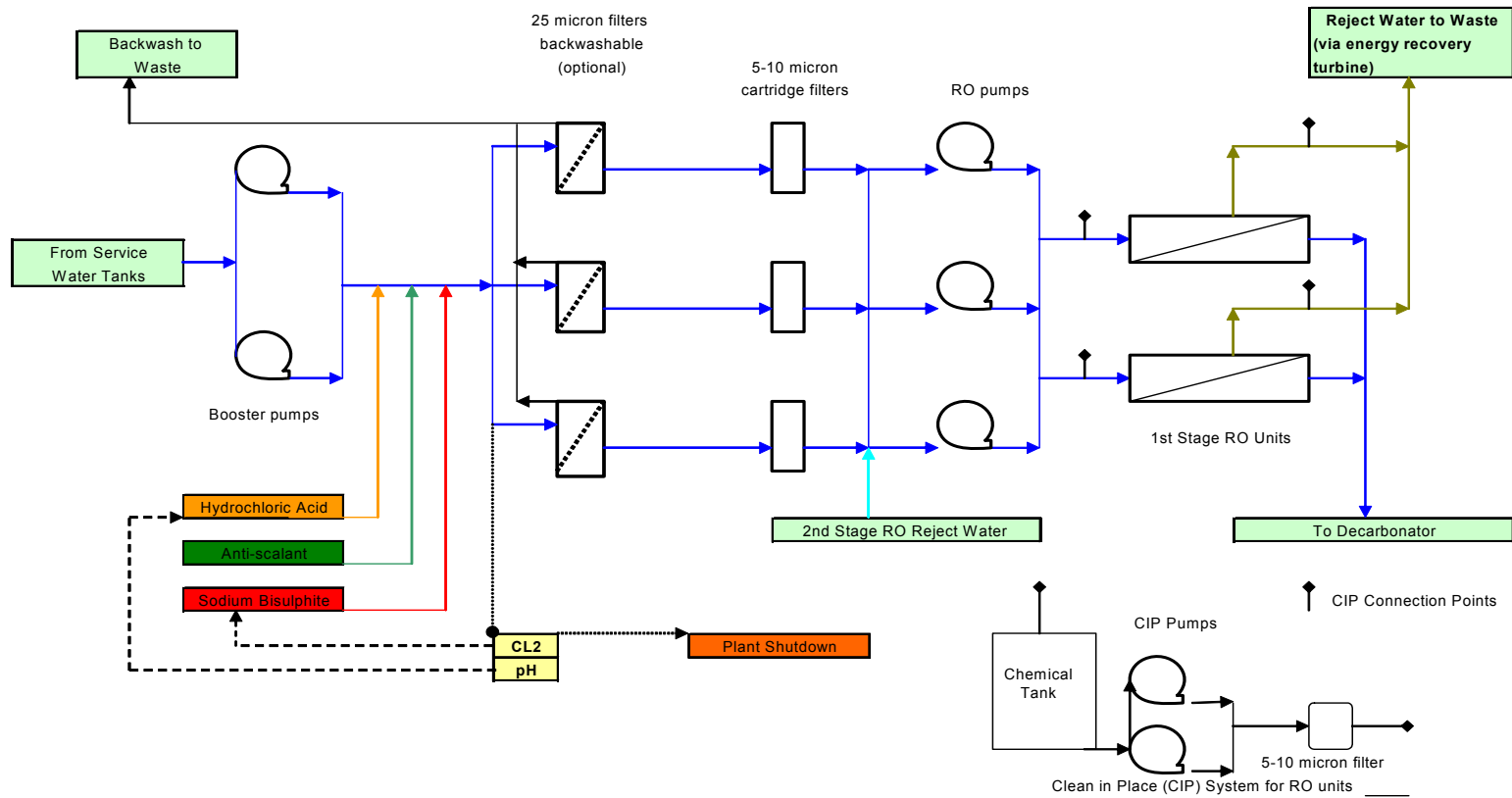
**Table 9.5 : Summary of River Water Composition**

Parameter	Maximum Value
Conductivity (at 25°C)	0.10 $\mu\text{S/cm}$
Ionic silica	5 $\mu\text{g/l}$ of $\text{SiO}_2$
Total silica	20 $\mu\text{g/l}$ of $\text{SiO}_2$
Sodium	5 $\mu\text{g/l}$ of Na
Potassium	5 $\mu\text{g/l}$ of K
Chlorides	1 $\mu\text{g/l}$ of Cl
TOC	<200 $\mu\text{g/of C}$

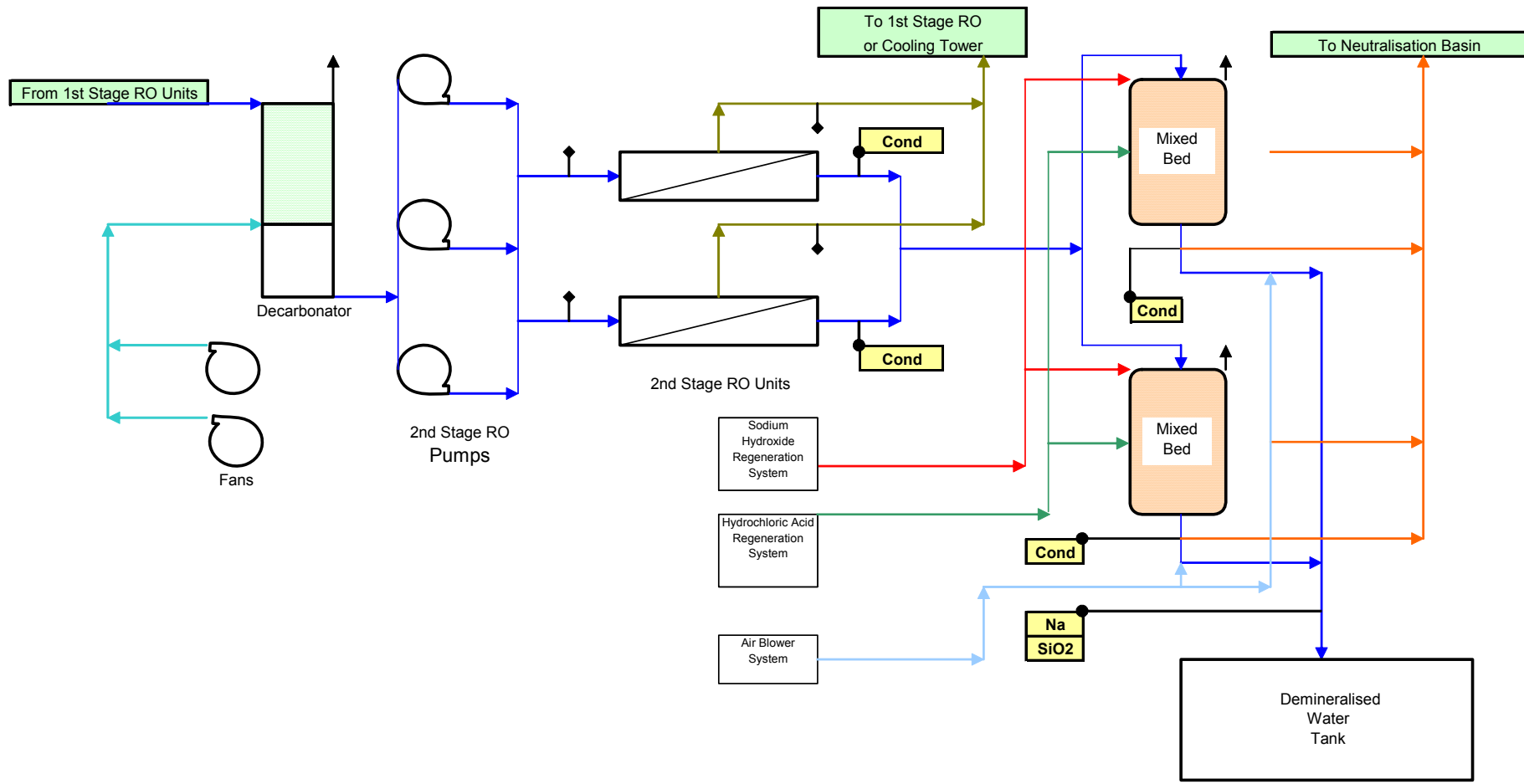
**Table 9.6 : Quality Requirements for Deionised Makeup Water**

Due to the overall poor quality of the river water and high variability in suspended solids, conventional coagulation and flocculation followed by pressure sand filtration was adopted as pretreatment for all river water abstracted for use in the power plant. The clarified water was then used as feed water to the makeup water treatment plant which was based on reverse osmosis membrane systems with mixed bed ion exchange polishing to achieve the required quality. The variability of the salinity of the river water meant that two stages of reverse osmosis were used to accommodate periods of both extremely low and high salinity. In periods of low salinity, the second stage reverse osmosis plant is bypassed and the permeate is fed directly to the mixed beds.

The makeup plant comprises of 2 x 50% reverse osmosis streams with two stages and 2 x 100% mixed beds. A common degasser is located between the two stages of reverse osmosis. The first and second stages of reverse osmosis in each stream contain 7 and 3 pressure vessels respectively, each with 5 standard membrane elements. The first and second stage reverse osmosis plant are designed for 70% and 80% recovery respectively with a design product flow of 36m<sup>3</sup>/hour from the mixed bed. A schematic of the makeup plant is shown in Figures 9.8 and 9.9.



**Figure 9.8 : Process Flow Diagram of 1st Stage Reverse Osmosis System  
(Courtesy of E.ON UK)**



**Figure 9.9 : Process Flow Diagram of 2nd Stage Reverse Osmosis and Mixed Bed System (Courtesy of E.ON UK)**

## **10 CURRENT STATUS OF WATER TREATMENT TECHNOLOGY OF COOLING WATER SYSTEMS**

### **10.1 Cooling Water System Operation**

The primary function of all cooling water systems is to remove unwanted heat. For an open recirculating water cooling system with a cooling tower, the operating principle is relatively simple. The cooling water is pumped through heat exchangers or, in the case of the main cooling water system, through condensers where the cooling water is increased in temperature. The warm water is then returned to the cooling tower where it flows into a distribution system located some height above the tower basin; 10 –13 metres for a larger cooling tower. The distribution system consists of numerous spray devices which break up the water into small droplets. These droplets then fall through a system of packing material designed to provide a high surface area on which the warm water droplets will form a thin film. This thin film of water comes into intimate contact with an upward current of cold air to which the heat is transferred. Thus, the heat is lost by evaporation to atmosphere. The upward current of air may be either natural draught or forced/induced circulation by large motor driven fans. The cooled water is then collected in the tower basin for recirculation by pumps to the heat exchangers.

In recirculating tower cooling systems, about 1% of the recirculating water is lost continuously through evaporation. The natural draught cooling towers at a typical 2000MW power station in the UK evaporate approximately 2,500m<sup>3</sup>/hour (assumptions: full load, 10°C gain, 70% relative humidity), which can rise to 3,500m<sup>3</sup>/hour in the summer.

As the water vapour leaving the tower is essentially free from salts, any impurities within the cooling water are concentrated. Several ionic salt species that are initially soluble in the make up water can be precipitated onto the heat exchanger surfaces as the temperature and concentration of the cooling water increases. In practice, the system is purged, or blown down, to limit the circuit concentration factor, where:

$$\text{Concentration factor, } C_f = \frac{\text{Concentration of salts in cooling water}}{\text{Concentration of salts in makeup water}}$$

The make up and purge systems at these plants are designed on the basis of allowing the concentration factor to be nominally 1.5. To maintain this concentration ratio, a make up flow of 7,500m<sup>3</sup>/hour and a purge flow of 5,000m<sup>3</sup>/hour is necessary.

A modest reduction in make-up water can sometimes be possible if the system can be operated at a higher concentration factor. In Table 10.1, a 30% saving is illustrated by operating at  $C_f = 2.0$ . This is the approximate limit for inland UK stations if the cost of water treatment is to be avoided to control scale formation.

Circuit concentration factor, Cf	Evaporation rate (m <sup>3</sup> /hour)	Purge rate (m <sup>3</sup> /hour)	Make-up required rate (m <sup>3</sup> /hour)
1.5	2,500	5,000	7,500
2.0	3,500	2,500	5,000

1. Figures based on a typical 2000MW coal-fired power plant in the UK

**Table 10.1: Tower Cooling System Make Up Water Requirements**

As the concentration factor increases, some of the dissolved solids in the recirculating water approach the limit of their solubility in water. This effect is especially significant for dissolved mineral salts which form insulating scales and deposits, e.g. salts of calcium, as these salts frequently become less soluble as the temperature of the recirculating cooling water increases. Thus, they tend to precipitate in areas of elevated temperature and lower water velocity, such as on heat transfer surfaces of critical heat exchanger systems. Insulating mineral scales are undesirable as they interfere and reduce the efficacy of the heat transfer process. Fouling of the heat exchanger surfaces of condensers can result in high cost penalties due to losses in overall power plant cycle efficiency, reduced generation and additional chemical cleaning requirements.

To prevent the formation of scaling conditions, the concentration factor within an open recirculating cooling water system is carefully controlled by bleeding or purging (blowdown) a portion of the concentrated recirculating water from the system and replacing with less concentrated makeup water. The concept of concentration factor is an important consideration in the operation of open recirculation cooling systems. The greater the concentration factor, the less water the system must lose through blowdown.

Both within the UK and US, large fossil fuel power plants with open recirculating system generally operate with a concentration factor typically in the range 1.25 – 2.5. The actual value depends on the chemical composition of the makeup water and any chemical conditioning regime employed to prevent scale formation.

The potential for scaling primarily depends on the calcium and alkalinity levels of the makeup water. Acid dosing of the recirculating water is generally used as the primary preventative measure for scale formation. The solubilities of scale forming salts, such as calcium carbonate and calcium phosphate, increases with decreasing pH and alkalinity. Thus, acid dosing to control the pH of the cooling water is a simple and cost effective option to reduce scaling potential of these calcium salts. However, reducing the pH of the cooling water increases its corrosivity to all components in the cooling water circuit. Therefore the pH of the cooling water must be strictly controlled and should never fall below 7.0.

The choice of acid for pH adjustment is dictated by environmental and economic factors. Sulphuric acid is generally used for this application as it is relatively cheap and its use is normally environmentally acceptable. Overall, acid dosing is a relatively low capital option but has high operational costs.



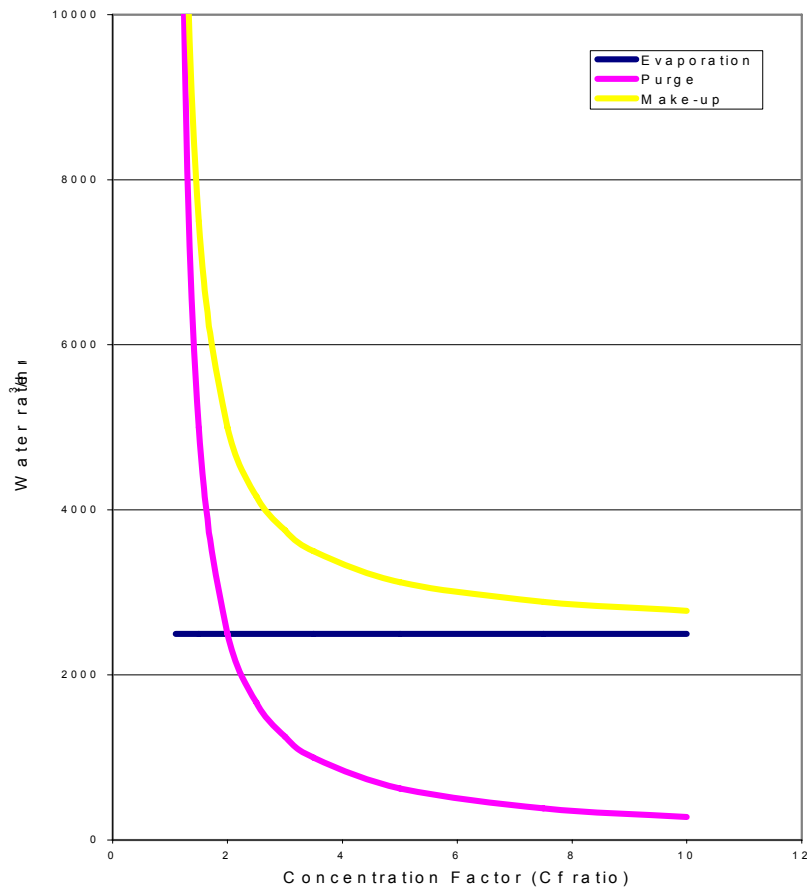
Additional protection from scaling may be attained through the use of a number of proprietary antiscalant additives available from industrial water treatment chemical suppliers. These additives are based on a variety of compounds including polymaleic acid, polyacrylates, polymethacrylates, polycarboxylic acids, phosphonates, non-ionic detergents and quaternary ammonium salts. These compounds are normally employed in substoichiometric quantities relative to the levels of calcium present in the cooling water. They function by modifying the crystal structure of the salts precipitating from super-saturated solutions so that scaling does not occur.

Antiscalant additives represent a low capital cost option as they are simply injected into the cooling water circuit. However, they are expensive, compared to mineral acids, despite being used at a comparatively low dose rates. Hence, in large power plant, they are seldom used due to the large volumes of cooling water that would have to be treated and the incumbent high chemical costs, even at the specified low dose levels.

Consequently, usage of these products tends to be restricted to cooling water systems of small CCGT and CHP plant. Their use, in conjunction with acid dosing, confers a greater tolerance to any excursions in cycles of concentrations which could give rise to scaling conditions if only acid dosing was employed. This is a particular advantage for the smaller power plants which generally have no plant chemist on site to supervise the cooling water chemistry. Another potential advantage of antiscalant additives is that higher cycles of concentration, up to a value of 3, may be obtained. Operating at concentration factors reduces the requirement for blowdown and makeup water. This may be beneficial to power plants facing restrictions on cooling water abstraction or discharge.

## **10.2 Operation at High Concentration Factors**

Where the availability of water for cooling system use is limited or there are environmental restrictions on the quantities of water discharge, it may be necessary to operate cooling towers to a much higher level of cycles of concentration. Operating a cooling water system at high concentration factors offers significant scope for water savings through reduced make-up water and purge flows. This can be seen from Figure 10.1, which shows the relationship between evaporation, make-up and purge rates with cooling water circuit concentration factor.



**Figure 10.1 : Relationship Between Cooling Circuit Concentration Factor and Make Up Water Flow Rates (Courtesy of E.ON UK)**

The main problems associated with high concentration factor operation are:-

- the concentration of dissolved salts and increased scaling risk; this may necessitate increased chemical dosing or hardness removal;
- suspended solids become more concentrated; this may involve increased cleaning costs or require other control measures such as side-stream filtration;
- for some waters with significant chloride content, the concentrated cooling water may become significantly more corrosive;
- biological control of the cooling water can become increasingly difficult at higher concentration cycles; this may necessitate increased biocide dosing which, in turn, may increase the corrosion propensity of the cooling water.

To achieve this goal of operation at high concentration factors it is necessary to substantially reduce the levels of hardness salts and alkalinity present in either the makeup water or the circulating cooling water in order to prevent scaling problems. The most common methods used are discussed below.

### **10.3 Cooling Water Softening**

Cooling system concentration factors are generally limited by the concentrations of potentially scaling calcium and magnesium hardness salts and silica in the recirculating water. Influent water and sidestream precipitation softening are widely used methods for the removal of these species from cooling water, enabling the cooling system to operate at much higher concentration factors than would otherwise be practicable. Concentration factors of 5 – 15 are reported typically with cooling water softening processes. Precipitation softening/clarification has the additional benefit of reducing the concentrations of metals and suspended solids in the cooling water. Note that ion exchange, in the form of base exchange, is not suitable normally for the direct softening of concentrated cooling waters.

A major disadvantage of influent softening is the large volume of water that must be treated. Treatment of a small flow from the cooling tower in sidestream softening is often sufficient to maintain the cooling water chemistry limits, even at high hydraulic cycles. Additionally, more efficient removal of calcium and magnesium can be obtained by firstly concentrating the salts in the tower. However, the precipitation efficiency of side stream softeners can be reduced at high concentration factors due to solubility effects with high levels of dissolved salts. Therefore, in these applications, the maximum recommended concentration of dissolved salts in the softener feedwater is approximately 12,000ppm, or a conductivity of 15,000 $\mu$ S/cm.

Softener/clarifier applications generally operate reliably under steady state conditions. However, process upsets can have an adverse effect on treated water quality, often resulting in the carryover of suspended solids. Upsets can be caused by sudden plant load changes or frequent plant start ups and shutdowns, which affect both the temperature and chemistry of the cooling tower blowdown. Problems with softener operation have also been experienced following changes in raw water composition. Mechanical problems can also occur due to the large volumes of sludge produced that require handling.

#### **10.4 Pretreatment of the Makeup Water**

The most common external treatment of makeup water for open recirculating systems is cold lime softening process. This removes hardness and alkalinity of the water, thereby reducing the potential from calcium carbonate scaling. The softened water can be used directly or blended with raw water to produce a desired level of calcium in the cooling water makeup. In some power plant, water softening is undertaken using base exchange softening. Again, this softened water can be used directly or blended with raw water. The use of very low or zero hardness makeup water is generally not desirable as the water tends to be corrosive to many metal components within the cooling water circuit.

Reclaimed sewage effluent is finding increasing use as cooling tower makeup water. However, this water usually contains inorganic phosphates which can lead to calcium phosphate scaling problems in the cooling system. To overcome this problem, precipitation softening of the makeup water has to be used to remove the phosphate before it enters the cooling water circuit.

#### **10.5 External Treatment of the Recirculating Cooling Water**

Some cooling systems utilise precipitation softeners operating on a sidestream from the circulating water. Occasionally the full flow of the circulating cooling water may be treated in this manner. Depending on how these softeners are operated, they can be used to remove calcium, magnesium, alkalinity, phosphate, silica and suspended solids from the cooling water.

The primary objective in most cases is to minimise water use and protect the environment whilst operating the cooling system at maximum cycles of concentration with minimum or zero blowdown. Operation of cooling towers in this mode may also require the removal of silica and or magnesium to silica and magnesium silicate scale formation.

Treatment with antiscalants to prevent calcium carbonate and sulphate scale formation is expensive and is sometimes ineffective in water systems with high calcium and alkalinity levels and high cycles of concentration. An alternative treatment option is to allow the calcium salts to precipitate and use high levels of dispersants to prevent scale deposition on heat transfer surfaces. In this option, sidestream filters on the recirculating water are used to remove these and other suspended solids from the cooling water.

#### **10.6 Suspended Solids Control**

Generally, the level of suspended solids in river water is acceptable for its direct use in a cooling system without any form of pre-treatment being necessary. To prevent large pieces of debris from entering the cooling water system, coarse screens are employed at the power plant inlet.

If high levels of water-borne suspended solids, in the form of silt, clay and sand, are present in the river water it may be necessary to control their deposition within the

cooling water circuit in order to prevent fouling of the cooling tower packing and heat exchanger surfaces.

The most common and cost effective approach for controlling deposition of suspended solids is to use polymeric dispersants. Most naturally occurring suspended solids contain negative surface charges. Low molecular weight anionic polymers adsorb on the surface of these suspended particles, increasing the overall net negative charge. This consequently increases the electrical repulsion between the particles, preventing them from agglomerating and settling. In this way, the suspended matter can be stabilised and kept in suspension prior to it being removed from the cooling water system via blowdown or sidestream filters.

Where river sources contain substantial amounts of suspended solids, it may be necessary to clarify the water before use. Clarification of the water may be undertaken using standard media filtration or a combination of coagulation and filtration, depending on the level of suspended solids present.

### **10.7 Control of Biological Fouling**

Cooling water obtained from rivers and sea will contain micro-organisms that will tend to grow and propagate within the cooling water system. For river sourced cooling systems bacterial slimes, algae and fungi will form in the cooling circuits. The growth of macro-organisms such as mussels and other marine shellfish can occur in seawater sourced cooling systems when they enter the system in the larval stage.

Micro-organisms can form fouling films on heat transfer surfaces such as condenser tubes. Algae can grow within cooling towers leading to screen blocking, reduction in air flows and overall decrease in cooling efficiency. Fungi can cause serious damage to cooling tower wood. In seawater cooling systems shellfish can restrict flows in intake culverts and block the inlets of condenser tubes.

To control biological fouling in cooling systems, biocides are generally added to the cooling water circuit. The most common biocide used is chlorine, either in the form of chlorine gas dissolved in water or as sodium hypochlorite solution. Due to the hazards of storage and handling of liquid chlorine from which the gas is obtained, use of sodium hypochlorite solution is the preferred option. At many inland power plants, chlorination of the cooling water circuits is carried out on an intermittent basis. For sea water power plant where fouling potential are high, continuous chlorination is practised.

Generally, sodium hypochlorite solution is purchased in tankers from chemical manufacturers as a 12 -15% available chlorine solution. This solution is dosed into cooling water circuit through the use of pumps or injectors. Alternatively, sodium hypochlorite solution can be produced on site by electrolysis of brine (salt) solution. Electrochlorination systems located at sea water power plant use the sea water to produce sodium hypochlorite solution.

Electrochlorination cells can be designed with electrodes of either concentric tube or parallel plate arrangement depending on the manufacturer. Sea water flows through several cells connected in series to produce a solution containing a sodium hypochlorite concentration of 1000 – 2000mg/litre equivalent chlorine. Higher concentrations tend to

reduce efficiency. The efficiency of the electrochlorination process is also affected by salinity, temperature and current density. Electrochlorination of seawater results in the formation of insoluble magnesium hydroxide and calciferous deposits on the electrodes which have to be regularly removed by acid cleaning.

For smaller cooling water systems, other oxidising biocides such chlorine dioxide and bromine release compounds are frequently used. There are also a wide variety of non-oxidising microbiocides available in the form of proprietary products from water treatment chemical suppliers.

## **10.8 Alternative Technologies for Cooling Systems**

In this section, alternatives to wet evaporative cooling systems are briefly reviewed and discussed to highlight the potential for water saving and perceived advantages and limitations of the various methods.

Firstly, alternatives with evaporative loss as part of the main cooling process are considered.

This technology is closely related to conventional wet evaporative cooling towers, but which have the capability to operate with lesser quantities of make up water. The two types considered here are wet-dry hybrid cooling and adiabatic cooling.

Secondly, systems designed to operate substantially dry are considered; e.g. dry cooling towers, including the Heller system, and Air Cooled Condensers. In dry cooling technologies, the main cooling load is without evaporative water losses

### **10.8.1 Hybrid Cooling Towers**

Whilst hybrid towers do employ a fraction of dry cooling, it is not normally sufficient to make any significant impact on the water consumption.

The common forms of power plant hybrid cooling towers are built with conventional evaporative cooling sections together with a dry cooling section formed with finned tubes. The quantity of cooling water evaporated is in proportion to the range or temperature drop in the evaporative section, so that the scope for water saving is indicated by the proportions of heat rejected in the two sections. For a typical tower range of 10°C, 1 - 2°C may be the temperature change in the dry section, with the balance of 8°C in the wet section. This results in an evaporation rate which is still 80% to 90% of a wet tower.

In typical European climates, the tower would be operated in the fully wet mode in summer, when the potential for evaporation tends to be higher. This tends to diminish any water saving advantage.

### **10.8.2 Coolers Employing Adiabatic Cooling**

In adiabatic coolers, the process coolant, either water or water-glycol mixture, is recirculated through the condenser in a completely sealed tubing system exposed to a

cooling air flow. Water is then sprayed onto the external surfaces, resulting in an additional cooling effect. Where circumstances permit, the system can be operated wet in summer and dry in winter with consequent water saving.

One major supplier of cooling equipment has developed this approach to offer a package cooler combining three sections and three operating modes: wet-dry hybrid, adiabatic and dry. The first two modes would both evaporate less water than an equivalent wet tower and the dry mode requires zero make-up. Experience is somewhat limited to date, but make-up water savings in the order of 70% are claimed.

### 10.8.3 Dry Cooling Systems

This section deals with cooling technologies in which the main cooling load is without evaporative losses. Whilst these types of systems are nominally dry, there may be issues with auxiliary plant cooling and peak cooling that leads to the augmentation of the power plant cooling needs by a small continuous or intermittent use of evaporative cooling and consequent water make-up and purge. Auxiliary plant cooling is discussed in a separate section.

The Heller system utilises indirect cooling with spray condensation. Exhaust steam from the turbine is condensed by a spray of cold water. The hot mixture is then cooled in finned tube bundles in a natural draught cooling tower. A proportion of the recirculating water is drawn off from the condenser sump and pumped to the boilers. A plant of this type was successfully operated in the UK at Rugeley Power Station.

In indirectly cooled plants with surface condensers, the cooling water flows through the condenser tubes and rejects heat in finned tubes in a natural draught cooling tower.

In air cooled condenser plants, the LP exhaust steam is discharged via large diameter pipework to arrays of A-framed finned tubes and condensed.

In hot dry regions, e.g. the Middle East, dry systems are used, but to enable an economically sized and technically acceptable design to be built for the whole year, so called peak coolers are employed with evaporative cooling for the very hottest periods. It is important to note that even nominally dry cooled plants may still have issues with water consumption and liquid effluents.

### 10.8.4 Dry Cooling and Plant Economics

Whilst dry cooling is an attractive means to minimize power plant water issues, dry cooled plants have characteristics that can adversely affect plant performance, which should be recognised at the project planning stage.

There are two very important differences between wet and dry cooled systems in the way they respond to ambient conditions. Wet systems have the potential to attain lower cold water temperatures than dry systems or, alternatively, can achieve comparable performance to dry systems with smaller, less costly, cooling plant. Wet system performance is governed by the ambient wet bulb air temperature, whereas the dry system is governed by dry bulb temperature, which is normally several degrees higher in a dry climate. Wet bulb temperature tends to be more stable, whereas dry bulb

varies over a wider range. Consequently, the capacity and performance of dry cooled plants can show large variations over a few hours. An additional characteristic of air cooled condensers is their sensitivity to performance impairment due to hot air recirculation, which is a function of wind direction and plant layout. Due to the higher elevation of the discharge, the natural draught variants are effectively immune to recirculation.

#### 10.8.5 Case Study : Eskom Experience

Eskom in South Africa have a number of years of successful experience in the operation of two types of very large dry cooling systems, e.g. dry towers at Kendal and air cooled condensers at Matimba.

In the Kendal plant (6 x 686MW units), condensation of LP steam is conventional in a surface condenser and the water is cooled in finned tubes in A-frames arranged inside a natural draught shell. Draught is generated in the usual way; no fans are used. Whilst the Kendal system requires a large inventory of 600m<sup>3</sup> of demineralised water, losses and make up are negligible and there are no concentration / blowdown issues. It is assumed that chemical conditioning of the demineralised water is necessary to prevent circuit corrosion.

In the South African climate, a dry cooled system requires some 0.8litres/kWh make up water, compared with 2.5litres/kWh for a wet-cooled system. In contrast, evaporation losses in conventional wet cooled plant account for approximately 80% of the total water used and, in a dry area like the South African high veldt; this could amount to 1.2million litres/hour for each 600MW cooling tower.

Eskom have also operated a cooling system similar to the former Rugeley A (UK) dry tower with a spray condenser.

Unfortunately, there is no information available as to how the auxiliary plant was cooled at Kendal.

#### 10.8.6 Turbine Auxiliary Plant Cooling for Dry Cooled Stations

Dry cooling offers scope for very large savings in water abstraction and discharge to the environment. However, if dry cooling is to be considered for a power plant, special consideration needs to be given to the auxiliary cooling requirements. Dry cooled auxiliaries would be considered unsuitable for some power plants for the following reasons:

- With dry auxiliary cooling, there are concerns about the effect of high cooling water temperatures on the auxiliary plant systems. In particular, high cooling water temperature would lead to reduced lubricating oil viscosity and high journal and thrust bearing temperatures. A change of oil temperature of a few degrees can alter the shaft dynamic behaviour of a turbo-alternator.
- A number of CCGT power stations in the UK with dry-cooled auxiliary systems have experienced operational problems during summer. In the case of Rye House PS (715MW CCGT), which has an air-cooled condenser, wet towers are used to cool



the auxiliary plant, which has enabled satisfactory control of auxiliary plant temperatures. The wet cooling system at Rye House circulates approx. 300kg/s and evaporates water a rate of approximately 7m<sup>3</sup>/hour.

Therefore, even in UK conditions, where air cooled condensers have been operated successfully, it is still considered best to support critical cooling functions, e.g. turbine lubricating oil coolers, with wet evaporative cooling.

## **11 CURRENT STATUS OF TECHNOLOGY FOR THE TREATMENT OF FGD AND IGCC WASTEWATERS**

### **11.1 FGD Wastewater**

An outline of a generic waste water treatment system for an FGD plant is shown in Figure 11.1.

The purge to waste comes from the overflow of the secondary cyclones of the FGD plant and, therefore, contains an amount of finely suspended gypsum particles, as well as other fine particulate insoluble material, plus dissolved metals, all in a background of soluble calcium chloride saturated with calcium sulphate (gypsum).

#### **11.1.1 Precipitation and pH Adjustment**

The first stage of treatment is chemical precipitation, followed by coagulation / flocculation, where the soluble metals are precipitated and the combined gypsum particles and precipitated metals are captured in the floc.

Lime slurry is added first, to raise the pH and precipitate metals as their insoluble hydroxides. The solubility of metal hydroxides varies with the metal and the pH of the solution; therefore, it is not possible to reduce all metals to their discharge limit concentrations by this procedure. Any soluble fluorides will be precipitated as calcium fluoride, although most fluorides should have reacted with the limestone in the absorber. Lime slurry is used for low cost compared to the sodium hydroxide alternative. A second stage precipitation is carried out by sulphide, either sodium sulphide or, preferably, an organo-sulphide, tri-mercapto triazine. Sulphides of metals, including mercury, are extremely insoluble.

#### **11.1.2 Flocculation and Coagulation**

A coagulant is then added to form a micro floc which captures the fine particulates and precipitates. The poly-electrolyte is added to assist the formation of larger floc particles which will settle under gravity. The suspension of floc particles is then passed into a settler, where the floc settles as sludge and clean water is taken off for subsequent filtration. Sludge settlement may be by a circular scraper settler, or a lamella plate separator. Alternatively, there could be dissolved air flotation where the sludge is taken to the surface of the vessel by air bubbles, where it is skimmed off, and clean water is taken from an underflow.

Multi media filtration removes the last traces of particulate matter and the water is transferred to a final storage tank or basin. A final pH adjustment stage, acid dosing, is included to meet the typical pH 6 – 9 discharge limit. This may be achieved by recirculation around the storage tank. This tank also provides filter backwash water. The waste from filter backwash is recycled to the front of the waste water treatment plant.

The pH adjustment, precipitation and coagulation / flocculation stages are generally a series of linked tanks, each overflowing into the next, with constant agitation and controlled chemical addition. The flow rate is fairly critical, so if the flow is likely to be

variable there may be some recirculation back to the head of the plant. Exceeding the design flow will often result in carryover of floc onto the filters, exceeding their design filtration capacity.

### 11.1.3 Sludge Thickening and Dewatering

The sludge is extracted from the settler by intermittent pumping to a sludge thickener. Sludge entering the thickener has only 2 – 4% solids content. In the thickener it is concentrated by further settlement, and addition of chemicals, to achieve around 10 – 20% solids content. The high solids of the FGD sludges give them lower moistures than typical flocculation sludges from make-up water treatment plants.

This thickened sludge is still easily pumped and can be either directly fired to a boiler as a slurry or it can be transferred to a sludge dewatering system. However, firing of the sludge as liquid slurry will recycle the 30,000mg/l chloride in the water phase back into the furnace gases and so into the absorber and back to the waste water treatment plant. Dewatering could be by a vacuum belt filter or a filter press. Vacuum belt filters will achieve 50 - 60% dry solids, filter presses will achieve 60 – 70% dry solids.

This outline design for a WWTP is a single stage process. All treatment chemicals are added to a continuous flow of water with one stage of flocculation to capture suspended and precipitated matter. Some plants have been designed on two stage flocculation, first for suspended solids and then for precipitated metals. This produces more sludge.

Depending on the design of the plant, the level of redundancy in equipment and the flow of FGD wastewater to be treated, typical capital costs for a FGD wastewater treatment plant for a standard 2000 MW power plant can range from £1.5 - 2.8 million. Due to the wide variation in chemical usage it is not possible to provide any typical operating costs.

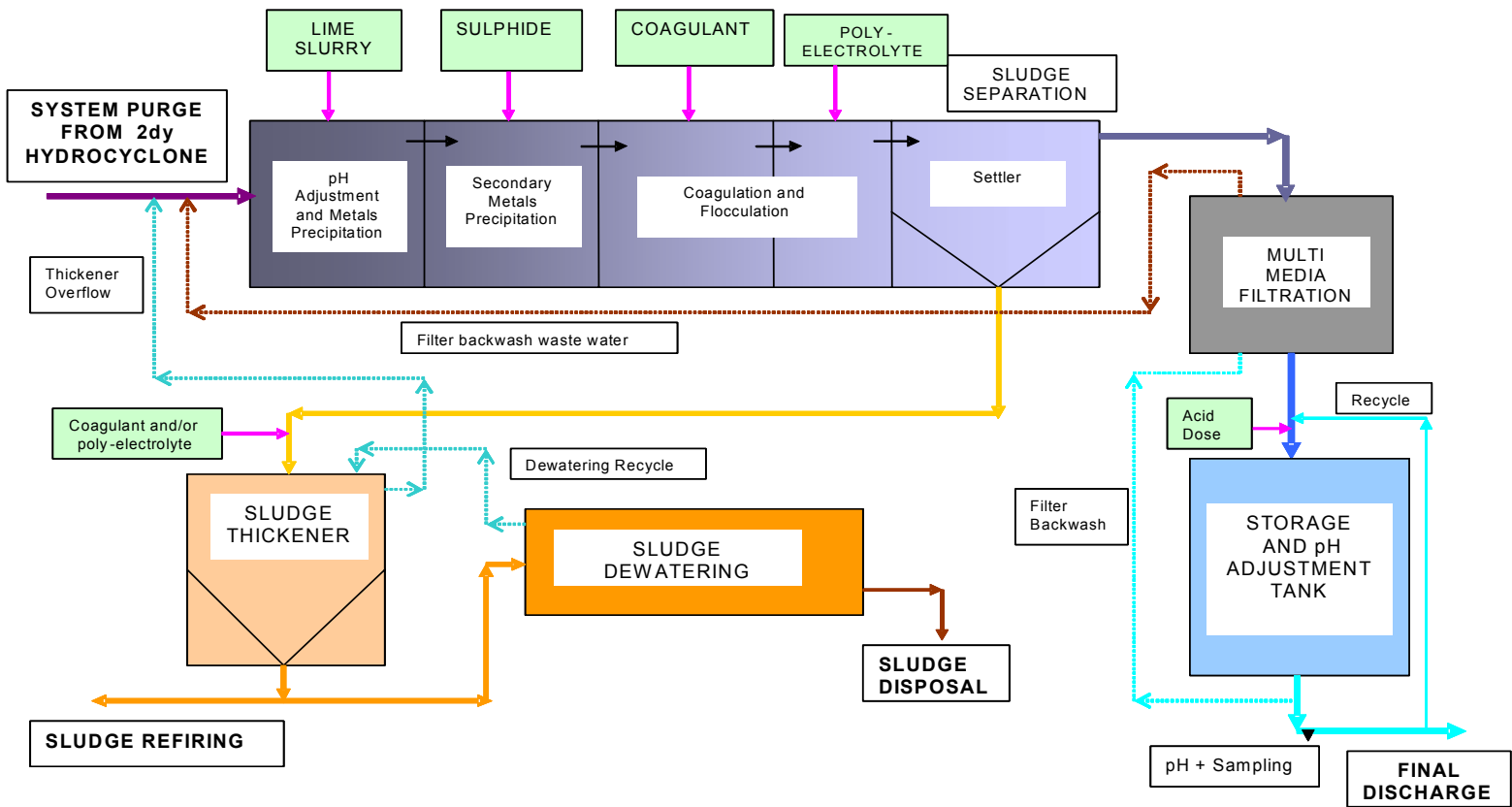


Figure 11.1 : Process Flow Diagram of Generic FGD Waste Water Treatment Plant  
(Courtesy of E.ON UK)

## 11.2 IGCC Wastewater

### 11.2.1 IGCC Process Description

The development of Integrated Gasification Combined Cycle (IGCC) allows both solid and liquid fuels to be used in CCGT plant. In the gasifier, the solid fuel, ie .coal, is partially combusted in a sub-stoichiometric atmosphere to form a flammable gas (syngas) which is cooled and cleaned, then fired in a CCGT plant. After several years of technology development and demonstration, this technology is approaching the status of commercial operation.

The concept of an IGCC power plant incorporates an oxygen or air-blown gasifier operating at high pressure and producing a raw gas, which is cleaned of most pollutants and contaminants and then burned in the combustion chamber of a gas turbine generator set for power generation. The sensible heat of the raw gas production process, along with the hot exhaust gas from its combustion in the gas turbine are used to produce steam. This steam is utilised to generate additional electrical power through a series of steam turbines. The main subsystems of an IGCC power plant are:

- Gasification plant including feedstock preparation system
- Raw gas heat recovery system
- Gas purification system with sulphur recovery
- Air separation unit (ASU), only required for oxygen-blown gasification
- Gas turbine with electrical generator
- Heat recovery steam generator (HRSG)
- Steam turbine system with electrical generator

The process of coal gasification for IGCC power generation can incorporate various gasifier designs, namely, fixed bed, fluidised bed and entrained flow bed.

The steam cycle of the HRSG in an IGCC plant is closely integrated with other plant components such as the gasifier. There are two HRSGs – one to recover heat from cooling of the product gas flow and one to recover heat from the GT exhaust. For such plant, in general, overall cycle efficiencies of around 43% can be achieved. A schematic showing a typical utility plant layout is shown in Figure 11.2

Since the 1950's, there have been 24 IGCC plants constructed or planned for construction throughout the world, based on several different designs. Of these 24, 3 have been dismantled, 17 are in operation and the remainder are under development.

In both the USA and Europe, IGCC plants have reached the commercialisation stage. In the USA there are currently two IGCC units generating electricity commercially - the United States Tampa Electric unit at Polk Power (250MW<sub>e</sub>) station and the Cinergy owned 260MW<sub>e</sub> plant at Wabash River. In Europe, three large scale IGCC (>250MW<sub>e</sub>) plants have been constructed and have operated successfully during the last few years.

The disadvantages usually associated with IGCC are reliability/availability and capital cost. Whilst the reliability/availability factor is improving (as illustrated by the efficient running of the Pernis plant in the Netherlands), the cost of IGCC plant remains high. The main benefit of an IGCC plant is its ability to allow coal to be fired in a clean and

efficient manner due to the removal of contaminants during the gas clean-up process. Coal is the largest fossil fuel resource in the world, so clean and efficient conversion technologies are of great interest.

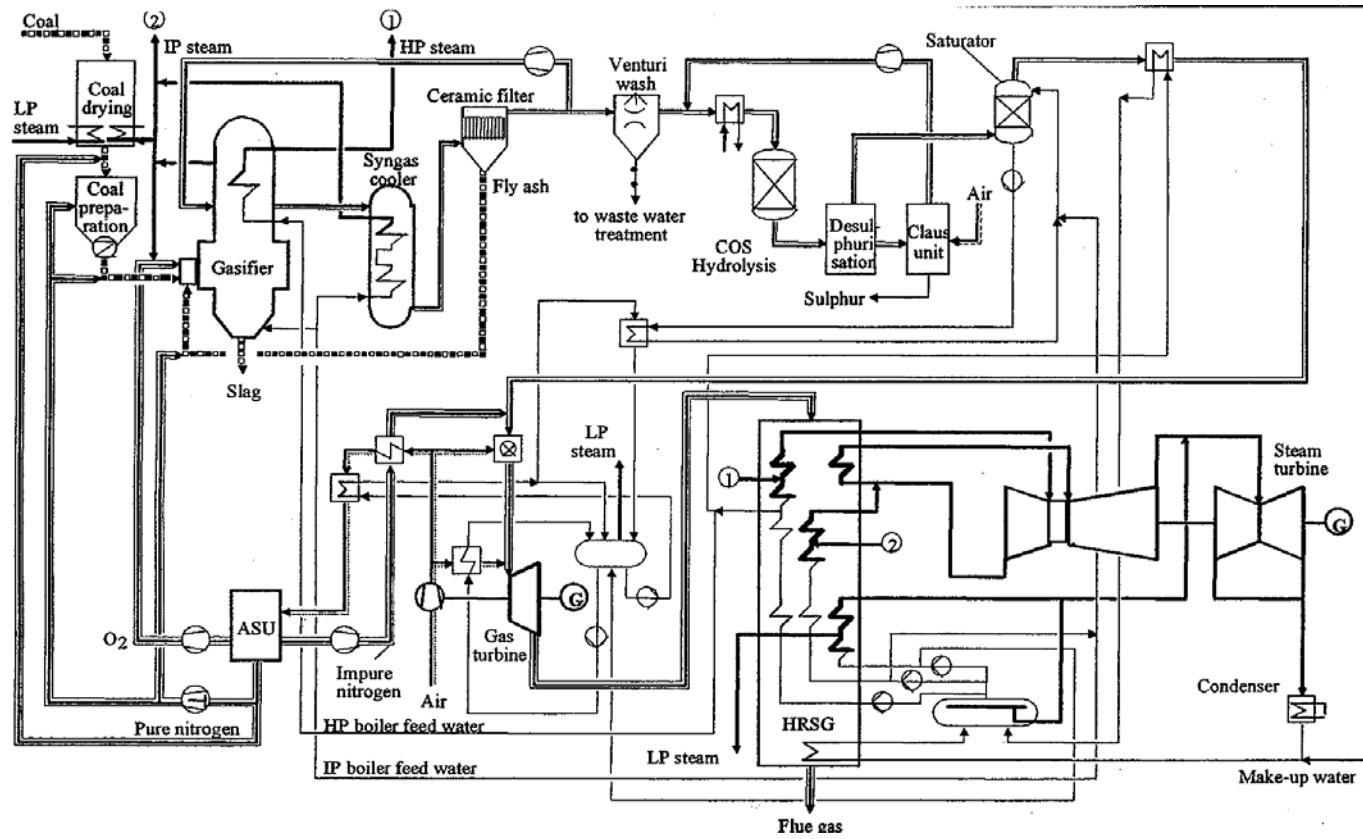


Figure 11.2 : Diagram of a typical IGCC plant (Courtesy of Siemens)

### 11.2.2 IGCC Wastewater Streams

IGCC power plants have two principal water effluents that are similar to those in conventional pulverised coal power plants.

The first is wastewater from the steam cycle, including drainage and blowdown from the boiler water/steam circuit, makeup water treatment plant effluent, and cooling tower purge water, if installed.

Gasification processes typically purify and recycle raw process streams and net wastewater discharge is normally only a process blowdown stream. This combined aqueous process effluent typically consists of four main process sources:

- Drainage water from the quenched slag
- Purge water from the water scrubber
- Condensate from the sulphur removal section
- Condensate from the Claus unit

The combined process effluents will contain high levels of dissolved solids and gases along with the various ionic species washed from the syngas, such as sulphide, chloride, ammonia and cyanide. In addition suspended solids, trace heavy metals and hydrocarbon by-products may be present

For entrained flow gasifiers, the high temperature employed in the gasifier results in the destruction of virtually all hydrocarbons, producing a wastewater stream with no appreciable organic content. Slag drainage water will contain mostly suspended solids and some dissolved trace metals. The filters upstream of the water scrubber will remove any entrained fly slag from the gas and this is collected as a dry solid. The filters will also remove a substantial proportion of the trace metals as they tend to be absorbed onto the captured fly slag. Hence, the other downstream wastewater streams will be almost completely free of solids and trace species. The water scrubber purge stream is very highly acidic due to the presence of significant quantities of HCl present

Depending on the process design, parts of the process effluent may be recycled to the coal feed preparation area, to the scrubber after entrained solids have been removed, to a zero liquid discharge water system or to a wastewater treatment system.

### 11.2.3 Wastewater Treatment

Typically, the wastewater treatment process consists of three main stages; coagulation/precipitation, steam stripping, biological treatment and evaporation. Coagulation and precipitation will remove heavy metals and suspended solids and adjust the pH to an acceptable level. Steam stripping is used to remove most of the volatile components, e.g. H<sub>2</sub>S, NH<sub>3</sub>, HCN. The biological treatment is intended to remove any organic species present, e.g. methanoate, and any remaining cyanide and ammonia species.

The coagulation and precipitation process will be similar to that used in the treatment of FGD wastewater. In general the heavy metals and suspended solids to be removed are contained within the "grey water" produced by the slag handling section and for this



reason it is normal for only this “grey water” to be treated by coagulation and precipitation. An advantage of this approach is that it considerably reduces the size of the coagulation/precipitation stage. As the slag drainage wastewater contain no other significant pollutants, the wastewater after this treatment is generally suitable for discharge to the aquatic environment. If discharge of the final treated aqueous effluent to the environment is not permitted then evaporation, using any of the various zero liquid discharge technologies (see Section 13.4) may be used to recover the sodium salts of chloride and fluoride present in the wastewater stream for subsequent disposal

The steam strippers used are similar in design to that used in the petroleum industry and usually incorporates a packed tower with spray nozzles. Aqueous effluent streams from the wet scrubber, the Claus unit and the sulphur removal stage are fed to the top of steam stripper and the combined wastewater is stripped by a countercurrent flow of steam introduced at the bottom of the stripper. The combined wastewater is strongly acidic which facilitates the removal of  $H_2S$  and  $HCN$ . However, the acidity of this wastewater prevents the removal of ammonia as it is present as a stable dissolved ammonium salt. Consequently, alkali is added part way down the stripping tower to convert the ammonium species to free ammonia which is then easily removed by steam stripping. The steam exiting the stripper is normally fed to the gasifier. The overall effect of the stripping process is that almost all of the  $H_2S$ ,  $NH_3$ ,  $HCN$  are removed from the wastewater.

Biological treatment is principally used to destroy any organic species present, e.g. methanoate, and any remaining ammonia and cyanide. The most common treatment method is aerobic oxidation which utilises the action of microbiological organisms to metabolise these pollutants to harmless by-products such carbon dioxide, water and other simple metabolites. However, in this type of treatment process, the level of potentially toxic species must be maintained at low concentrations to ensure that they have no adverse or inhibitory effect on the biological oxidation process. Some of the more common biological treatments techniques are :

- Complete-mix activated process
- Membrane reactor process
- Trickling or percolating filter process
- Expanded bed process
- Biofilter fixed bed process

Following biological treatment the treated wastewater may be discharged to the aquatic environment or treated by a zero liquid discharge technology

## **12 POTENTIAL FOR FUTURE DEVELOPMENTS**

### **12.1 Deionisation by Ion Exchange**

The use of polymeric organic ion exchange resins for the deionisation of water is now a fully mature and developed technology. Modern ion exchange resins are stable high quality products which have made ion exchange a highly reliable process capable of producing high purity deionised water, even with poor pretreatment or when subjected to substandard operating practices.

Ion exchange currently remains the preferred and economic choice of treating water containing low total dissolved salts. However, the continuing development of low pressure high flux membranes continues to lower the total dissolved salts barrier at which reverse osmosis systems can be competitive with conventional ion exchange.

Whilst ion exchange still remains a viable option as full scale deionisation process for many water supplies, the technology does suffer from two potentially serious disadvantages in face of the strengthening competition from membrane technology. Firstly, ion exchange is unable to remove non-ionic species such as colloidal silica. Secondly, anion exchange resins are unable to fully remove all naturally occurring organic species from water sources and are themselves susceptible to fouling by the presence of organics leading to deterioration in their performance. The presence of both colloidal silica and organics in deionised makeup water supplies for high pressure boilers can pose a significant risk to the integrity and performance of power plant components.

The development of macroporous and acrylic anion resins has mitigated potential organic fouling problems. The problems with colloidal silica and organics has, historically, not been a major problem as most power plant tended to use relatively clean raw water supplies such as municipal or groundwater (borehole) in which these problematic species were generally low in concentration. The current trend for modern power plants is to utilise more low quality water which contain higher amounts of these species. Inevitably, these waters pose serious problems to ion exchange systems and reverse osmosis is the only practicable option for their effective removal of colloidal silica and organics.

Within the UK this trend has already been observed with two modern fossil fuel power plants retrofitting reverse osmosis system to their existing ion exchange plant as a consequence of the inability of ion exchange plant to fully remove organics present in the raw water supplies.

Whilst, ion exchange technology faces a serious threat from membrane technology as a result of these limitations, reverse osmosis alone is not capable of producing the required high purity deionised water. Thus, mixed bed ion exchange is commonly used to provide the polishing of the permeate to attain the desired quality. However, this niche is now under threat from the new and developing continuous electrodeionisation (CEDI) technology which now can produce similar water quality to that of a mixed bed ion exchange system. Earlier CEDI systems suffered from leaking seals and electrical arcing but CEDI manufacturers have been addressing such construction issues to improve reliability and performance.

There is no evidence from the main resin manufacturers that there is any serious resin development work being undertaken in the application area of general water deionisation for the power sector. The main thrust of research and development appears to be in the areas of speciality resins for other industrial sectors. Indeed, over the past few years, there has been a major rationalisation and reduction of the ion exchange resin grades available for basic deionisation.

Recent improvements in performance of ion exchange processes have been achieved through engineering developments rather than improvement in the resin ion exchange properties. The advent of uniform particle size resins has led to improving regeneration, reducing pressure drops, improving flow characteristics and better separation in mixed beds and thereby reducing cross-contamination. The packed bed generation of ion exchange heralded higher efficiency of regeneration with reduced chemical usage and waste water. Packed beds are also of simpler design providing lower equipment costs. Recently, a resin manufacturer introduced a new vessel water/chemical distribution system based on fractal technology. It is claimed this new distribution design offers near perfect plug flow conditions, thereby offering the potential to provide further improvements in both regeneration and bed capacity.

For the future, there appears to be no major innovation in ion exchange resin technology on the horizon which will provide further improvements in ion exchange resins to compete against the ever encroaching membrane technology. Any further improvements, if any, in the ion exchange process is likely to arise from further engineering advances of the ion exchange process to decrease chemical usage, wastewater production and maximise the inherent exchange capacity of the currently available ion exchange resins.

## **12.2 Reverse Osmosis Membrane Technology**

In contrast to ion exchange technology, reverse osmosis membrane technology is continually and rapidly developing with an ever increasing market. Recently, the development of low fouling composite membranes with equivalent or higher flux and salt rejection rates of the normal composite membranes has led to their use in the treatment of more difficult fouling waters.

Costs associated with the reverse osmosis process have markedly declined in recent years. These cost reductions have occurred through economies of scale and improvement in membrane technology in terms of increased salt rejection, increase flux rates and new materials.

It is considered that future technological advances in reverse osmosis will continue to reduce costs of water production by optimising performance. Research and development is likely to focus on lowering pressure and energy requirements, further increases in flux and salt rejection rates, new materials resistant to fouling and chlorine and more efficient energy recovery devices.

## 12.3 Other Membrane Technologies

### 12.3.1 Microfiltration Membranes

Whilst microfiltration membranes produce high quality treated water, they do rely on the efficiency of backwashing and periodic cleaning to maintain production and performance. The current use of microfiltration membranes is limited to waters containing relatively low levels of suspended solids compared to some types of water treated by conventional clarification processes.

Continuing research and development on membrane chemistry and morphology to better understand fouling tendencies is required. Development of hydrophilic membranes with improved resistance to natural organic matter, oils and organic dispersants/sequestrants will continue to improve the commercial viability of membrane technology in water treatment within power plant.

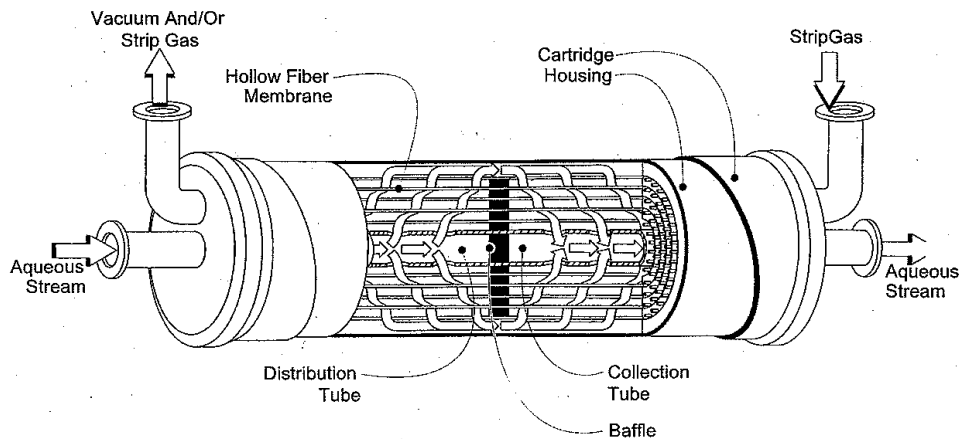
### 12.3.2 Continuous Electrodeionisation

Continuous electrodeionisation faces the same challenges as other membrane technologies such as reverse osmosis and microfiltration; lowering costs, improving reliability and increasing performance. Over the last few years there has been a shift towards “thick” cells as opposed to the earlier “thin” cell configuration. With this change and the adoption of a modular system approach, costs have been reduced. There are still a variety of methodologies used for the arrangement of the ion exchange material within the cell and further development is required improve the capability to remove silica and carbon dioxide that is normally present in reverse osmosis permeate.

Recent developments in CEDI module construction have improved both physical integrity and module reliability while simultaneously enabling process simplification such as elimination of concentrate recirculation and elimination of salt injection into the concentrate stream. However, reliable long term operation of CEDI system requires careful process design in particular with respect to the presence of hardness salts, silica and carbon dioxide in the feed to the CEDI.

### 12.3.3 Gas Separation Technology

Hollow fibre contained liquid membranes (HFCLM) have been used for gas separation through a nonporous polymeric membrane. Microporous polypropylene hollow fibres have been used as the membrane material. Gas separations such as  $N_2$ - $CO_2$ ,  $CH_4$ - $CO_2$ ,  $SO_2$ - $CO_2$ - $N_2$  and others have been studied by HFCLM technique. It is possible that this technology could be used as a replacement for traditional atmospheric degassers and also for deaeration of boiler makeup water. A typical membrane contactor is shown in Figure 12.1.



**Figure 12.1 : Gas Membrane Contactor (Courtesy of Celgard LLC)**

For carbon dioxide removal, purified air can be employed as the sweep gas. Substitution of nitrogen for air as the sweep gas allows for removal of dissolved oxygen. Application of vacuum also results in the removal of dissolved gases from water. A combination of both sweep gas and applied vacuum can enhance removal of dissolved gases from water streams.

## **12.4 Emerging and Novel Treatment Technologies**

### **12.4.1 Ultraviolet Light Technology**

For many decades, chemical addition, such as chlorine, chlorine dioxide, and organic biocides, has been the preferred treatment for disinfection. This is, however, changing, as the addition of chemicals poses problems with respect to such factors as increase in process salinity, safety factors in handling and storage, process control and overdosing, product contamination, and economics. The treatment of water through other techniques such as ozone, peroxide and/or ultraviolet light has been on an increase.

Ultraviolet (UV) light treatment of water is a physical technique whereby water is irradiated with light of specific wavelengths. UV disinfection technology has been around for a long time but never has been applied to power station water processes. Major advances have being made only in the last few decades include lamp manufacture technology with respect to output, wavelength spread and operating life, configuration design and monitoring.

UV light is part of the electromagnetic spectrum, situated between X-rays and visible light, with a wavelength between 100 and 400nm. The UV spectrum is split into a number of bands, namely, UV-A, UV-B, UV-C, and Vacuum UV. Each band is used in specific applications, with UV-C and parts of UV-B being used for disinfection purposes (between 200 and 315nm). Vacuum UV is associated with the oxidation of organic carbon.

For the germicidal treatment (disinfection) of water, UV-C is the most effective band of UV, killing microorganisms such as bacteria, viruses, fungi, mould, yeast and algae in

water, air and on surfaces. In general, wavelengths from 200 to 315nm are effective in disinfection, but to varying degrees, with the maximum at 265nm.

UV has also been used for the destruction of total organic carbon (TOC) compounds from water, the wavelength usually associated with this being in the vacuum UV band, around 185nm. This is of importance in the production and maintenance of ultrapure water.

UV is generated through the principle of mercury vapour discharge. The fluorescent tube has an electrode on either side of a tube filled with a slight amount of mercury and an inert gas. A high voltage pulse preheats the gases, after which the mixture is ignited. Sending a current through the tube between the electrodes produces a gas discharge. Emission spectra are produced from the fall from the excited state to the ground energy state of the mercury atom.

UV-C light is generated by lamps containing slight amounts of mercury, and is emitted through the combination of gas pressure and electrical current. Lamp technology can be divided into two types namely low pressure (0.001-0.01bar) and medium pressure (1-2bar).

Low pressure (LP) lamps typically emit monochromatic UV light at a wavelength of 254nm. These lamps are also temperature sensitive, having to operate at about 40°C. LP systems are easy to operate, and are often used in drinking water applications up to 200m<sup>3</sup>/hr.

Medium pressure (MP) lamps produce 10 to 20 times more UV power than low pressure lamps. MP lamps have a wide wavelength band, covering the total germicidal UV band, including the most effective DNA/RNA breaking wavelengths of 260-265nm, and the protein/ enzyme damaging wavelength around 220nm. Due to the high intensity of the lamps, water flows up to 3.000m<sup>3</sup>/hr can be treated with a single unit.

The use of UV radiation in conjunction with ozone or hydrogen peroxide can further enhance the efficacy of the overall oxidation process.

#### 12.4.2 Magnetic Ion Exchange (MIEX™) Process

The MIEX is a process for the removal of dissolved organic species and is a continuous ion exchange process.

The process consists of two main components -the MIEX resin and the specially developed process for using the resin. The MIEX resin is a micro size, macroporous, strong base, magnetic ion exchange resin, developed for the reversible removal of negatively charged organic ions. These characteristics result in a resin that is highly resistant to physical attrition and organic fouling. The resin also has a very small particle size with a mean particle diameter of only 180µm. While the specific surface area is comparable to other conventional macroporous resins, this resin has a greater external bead surface area. This benefits the exchange kinetics for dissolved organic removal and the resistance to fouling.

In addition to these features, the MIEX resin has magnetic particles incorporated within its polymeric structure. This means that each resin bead acts like a small magnetic particle capable of forming large agglomerates under the correct conditions. The MIEX process differs significantly from conventional ion exchange processes in a couple of ways. One difference is that the ion exchange process is carried out on a truly continuous basis with the overall ion exchange capacity within the process being continuously maintained at a predetermined level. This leads to consistent quality product water with a controlled level of dissolved organics.

The process consists of adding the magnetic resin to a continuously stirred tank (contactor). This tank is where the ion exchange occurs and has residence times in the range of 10-30min depending upon the water quality and performance required. From the stirred tank the water/ resin mixture flows to a gravity settling tank where they are separated with the treated water overflowing out of the settler for further treatment. Under the low shear conditions in the settler, extremely high efficiency recovery of the resin is obtained as the resin agglomerates and settles rapidly to the bottom of the tank. This resin is collected and pumped back to the stirred tank at the head of the plant for reuse. A small portion of this settler underflow (5-10%) is removed from the process and sent off to the batch regeneration process. To ensure that the ion exchange capacity of the plant is maintained an equivalent volume of fresh, regenerated resin is added back into the process to replace the 5-10% drawn off from the settler underflow.

Regeneration is performed by contacting the resin with a concentrated sodium chloride solution. After regeneration is complete this resin is stored in the fresh resin tank before further use.

### 12.4.3 “On Demand” Condensate Polishing

In an attempt to find a low cost alternative to current condensate polishing plant installations, the Electric Power Research Institute (EPRI) have proposed a radical conceptual approach described as “On Demand” condensate polishing (ODCP). In contrast to the fixed deep bed polishing plant that is widely used, ODCP is based on the concept of injection of ion exchange resin beads directly into the condensate system. The injected resin would be recovered from the condensate by hydrocyclones with a further downstream trail filter used to capture any resin not recovered by the hydrocyclones. It is envisaged that the resin would only be injected when condensate quality was poor and the resin would be dosed proportional to the level of impurities present. So far this concept has only reached the stage of feasibility assessment and much development work is required before a full scale commercial system is available.



## 13 WATER USE AT POWER PLANT

The power industry is a substantial user of water for plant processes such as condenser cooling, demineralised boiler make up water production and, at coal-fired plant, flue gas desulphurisation and ash- and coal-handling facilities. In most countries, the use of water at power plant is subject to extensive environmental legislation. Additionally, various factors are contributing to a greater interest in water conservation within industrial processes worldwide. In this chapter, environmental legislation applicable to water use at UK power plant is highlighted. Opportunities for water reuse at power plant are then considered more generally, including descriptions of technologies that are used to achieve 'zero liquid discharge' from sites.

### 13.1 Environmental Legislation

In the UK, the use of water by the power industry is subject to stringent environmental legislation set by national and European Law and international agreements. The main regulatory controls for power plant are outlined below.

#### 13.1.1 European Law

There are a number of European Directives relating to water quality protection and water habitat conservation of particular relevance to the power industry. These are listed in Table 13.1. Key directives for water use at power plant in the UK are discussed below.

Directive No.	Subject of Directive
76/160/EEC	Bathing water quality
76/464/EEC 86/280/EEC	Pollution by dangerous substances
78/659/EEC	Water quality for freshwater fish
79/923/EEC	Quality of shellfish waters
79/409/EEC	Wild bird conservation
80/68/EEC	Protection of groundwater against pollution caused by certain dangerous substances
90/313/EEC	Freedom of access to environmental information
92/43/EEC	Conservation of natural habitats and wild flora and fauna
96/61/EEC	Integrated Pollution Prevention and Control
2000/60/EC	Water Framework Directive

**Table 13.1: Selected European Directives Relevant to Power Plant Water Use**

#### Integrated Pollution Prevention and Control

Combustion sector installations are required to apply for Integrated Pollution Prevention and Control (IPPC) permits between 1<sup>st</sup> January and 31<sup>st</sup> March 2006. These will replace current Integrated Pollution Control (IPC) authorisations. All installations are required to have a permit in order to continue to operate.

The basic purpose of IPPC is to achieve a high level of protection for the environment as a whole through the introduction of a more integrated regulatory approach to controlling pollution from industrial sources. As well as emissions to air, water and land,

environmental impacts also covered include noise, energy efficiency and waste production. The permit conditions set by regulators are based on the use of 'Best Available Techniques' (BAT), which balances the costs to the operator against the benefits to the environment. The emphasis of IPPC is on preventing emissions and waste production and, where this not practicable, reducing them to acceptable levels. There is a requirement for operators to use BAT to prevent or minimise the release of prescribed substances to controlled waters, with concomitant controls applying to releases to public sewers.

At power plant permits, the maximum concentrations of pollutants that may be discharged to water over one or more periods of time are set by emission limit values (ELVs). ELVs are set on a case by case basis to achieve environmental quality standards (EQSs) for specific chemicals following mixing and dilution in the receiving watercourse. EQSs describe threshold concentrations below which no adverse impact on the aquatic environment in the receiving water is predicted.

#### Habitats Directive

The Habitats Directive requires high standards of protection to be applied to nature conservation sites identified to be of international importance. These sites are known collectively as 'Natura 2000'. IPPC permits will only be granted to power plant operators after demonstration that aquatic discharges have no adverse effect on the integrity of any downstream Natura sites. If, following appropriate assessment, it is not possible to ascertain that the integrity of the site will not be adversely affected, then permission may only be given where there are no alternative solutions and imperative reasons of overriding public interest.

#### Water Framework Directive

The Water Framework Directive (WFD) is the legislative instrument for the protection and improvement of surface waters (rivers, lakes, estuaries, coastal waters and ground waters) within the European Union. The WFD was established in December 2000 and EU Member States are required to ensure that all surface waters achieve the target of 'good status' with respect to ecological, physical and chemical quality standards by the end of 2015. The WFD is river-catchment based and each river will have a River Basin Management Plan (RBMP). The first river basin characterisation exercise (2004) showed that most waters are at risk, or probably at risk, of failing to meet one or more aspects of the good ecological status required by the Directive.

Under the WFD (Article 16), the European Commission has identified 33 'priority substances' (PS) that pose a significant risk for the water environment. These are listed in Appendix A. The proposed substances will be subject to emission controls and quality standards in order to achieve a 'progressive reduction of discharges, emissions and losses'. Within the list, 11 substances - those of particular concern - have been identified as 'priority hazardous substances' (PHS), for which discharges, emissions and losses will have to cease over a 20 year period. A further 14 substances are identified as being subject for review for identification as possible priority hazardous substances. A new Groundwater Daughter Directive has also been proposed recently for implementation around 2006, which would set maximum permissible concentrations (threshold levels) in ground water for a number of pollutants, including ammonium,

arsenic, cadmium, mercury, lead, sulphate and chloride. If approved, this will also oblige Member States to monitor and assess groundwater quality and to identify and reverse any upward trends in groundwater pollution.

The aims of the WFD and River Basin Management Plans can only be met by controlling emissions and abstractions at source and will have a significant effect on many industries. The exact impact that this will have on power plant is uncertain at present, but it is likely that power plant IPPC applications will be used to deliver Directive objectives.

#### Dangerous Substances Directive

The EC Dangerous Substances Directive 76/464/EEC covers discharges to inland surface waters, territorial waters, inland coastal waters and ground water. In 1980, the protection of groundwater was taken out of 76/464/EEC for regulation under the separate Council Directive 80/68/EEC.

The Dangerous Substances Directive introduced the concept of List I and List II substances (Appendix B). The purpose of the Directive is to eliminate pollution from List I substances due to their toxicity, persistence and potential for bioaccumulation and to reduce pollution from List II substances, which are considered to be less toxic, or the effects of which are confined to a limited area. The Council Directive 76/464/EEC is being integrated into the Water Framework Directive and List I substances have been replaced by a list of WFD Priority Substances. The rest of 76/464/EEC, including the emission reduction programmes, will remain in place until 2013.

#### 13.1.2 UK Statutes

The following statutes relate to England and Wales; there are separate - but broadly parallel - statutes for Scotland and Northern Ireland.

#### Abstraction Licensing

Any power plant in England and Wales wishing to abstract surface or ground waters for process use requires an abstraction licence from the Environment Agency. Included in considerations of applications will be available water resource and other demands upon it, e.g. abstractions for industrial, potable and recreational use and environmental and conservation requirements.

Whilst many existing power plant licences are licences of right that are not time limited, all new or modified licences will be. In new licence applications and for renewals, plant will also need to demonstrate continuing requirement for abstraction and efficient use of water at site.

#### Discharge Consents

Discharges into freshwater systems and estuaries are controlled by a system of consents determined and issued by the regulator (the Environment Agency in England and Wales). The consents set limits on the type, concentrations and allowable volumes of pollutants that can be released. Most power station discharges are dealt with separately under Integrated Pollution and Control regulations.

## 13.2 Pressures for Water Reuse

Various factors are contributing to a greater interest in water conservation within power plant and other industrial water consuming processes worldwide. These include:

- increasing pressures on water resources;
- compromised quality of water sources;
- increasingly stringent environmental legislation regarding water use;
- increasing costs of water abstraction and discharge.

These pressures are expected to have an increasing influence on water treatment decisions.

In general, pressures on water availability and water quality have typically been limited to plant located in arid or industrialised regions or at locations remote from viable surface or ground water sources to date. Whilst drivers for water conservation will continue to vary geographically, increasing limitations on clean water supplies are beginning to be seen, or are expected in the near future, in a number of countries worldwide. In emerging economies in particular, industrial plants have had difficulties with both availability and quality of raw water supplies. Heavy pollution is prevalent in many Asian countries and lack of adequate municipal water treatment plant means that industrial users will tend to receive poorer quality source water.

In order to reduce reliance on potable water supplies, increased use of alternative water sources at power plant is expected. Industrial wastewaters, brackish water, poor quality groundwater and seawater are all now viable options for treatment. The use of reclaimed municipal wastewater in power plant has seen particular growth over the last decade as a result of increasing limitations on water supplies.

Growing pressures on water availability and measures required to control industrial pollution have resulted in environmental control legislation becoming increasingly stringent. For power plant, pressures on water availability are making access to water more difficult and more expensive. Abstraction licences are becoming harder to obtain, with reductions in allowable abstraction volumes. Where discharge is allowed, regulations to control industrial pollution are requiring more onerous contaminant discharge limits, necessitating increasing amounts of on-site treatment.

Consequently, measures are increasingly being implemented by power plant to reduce both the amount of water abstracted for plant use and the amount of wastewater discharged. This is being achieved in a number of ways, including the optimisation of water use within processes and the application of water recovery and reuse schemes, particularly in new build plant.

The technical and economic feasibility of wastewater reuse schemes at power plant requires site specific consideration and will be dependent on the particular drivers and policy with regards to water use at any given location. Relevant factors include [1]:

- the quality, quantity and cost of raw water available to the plant;
- the quality and quantity of water needed for various plant processes;

- the ability to recycle wastewater streams to other plant processes, either directly or after suitable treatment;
- the wastewater treatment technologies available; capital, operational, maintenance and labour costs and floor space and construction requirements;
- environmental restrictions on the quantity and quality of any wastewater that may be discharged.

In general, the application of recycling normally requires some suitable process technology for water purification, or temperature reduction for the recovery of hot boiler waters. The treatment process necessary will be dependent on the quality and quantity of the wastewater and the purity requirements of the recipient process. The treatment costs incurred to enable water reuse may be offset by savings from reduced water abstraction, discharge, or raw water treatment. However, not all wastewaters will be viable options for recovery and reuse.

At power plant worldwide, reuse schemes can extend from the recovery of individual high quality waste streams, which can be reused either directly or after only limited treatment, though to the development of fully integrated water/wastewater treatment systems for zero liquid discharge (ZLD). Integrated water/wastewater treatment systems link together the cooling tower, demineraliser system and the ZLD equipment in order to minimise site water usage and maximise water recycling.

Zero liquid discharge (ZLD) plant designs are becoming more common place in the power industry, driven by environmental restrictions on discharges and limitations on water supplies. The concept of a “Zero Emission” power plant, which includes liquid wastes, forms a central part of the US Department of Energy’s “Vision 21” strategic programme for large scale generation technologies.

At present, ZLD sites are generally limited to arid regions of the USA, South Africa and Australia. In the USA, environmental regulations and lengthy permitting processes have resulted in many of the recently installed (1999-2002) CCGT plant adopting ZLD [2]. In some cases, this significantly eased and advanced the permit cycle, whilst in other cases, no other viable discharge options existed. The recent US CCGT plant build has been predominantly at greenfield sites, which has facilitated the development of integrated approaches towards optimisation of the overall water and wastewater treatment systems at sites, linking together the cooling tower, demineralisation system and ZLD equipment. This approach has afforded advantages of streamlined processes and simpler, easier to operate treatment systems when compared to conventional, segregated methods for minimising overall water usage and maximising water recycling. ZLD can also be achieved by water resource sharing, where power plant wastewaters can be reused in applications off-site, rather than discharging directly to waste.

### **13.3 Opportunities for Water Reuse**

In this section, the potential for wastewater reuse in the main power plant water consuming processes is discussed. The most common power plant wastewater streams recovered for reuse are boiler blowdown waters, demineralisation plant effluents, ash handling wastewaters and cooling tower blowdown. Whilst these waste streams are all produced internally by power plant processes, water reuse can also be considered as the reuse of effluent produced by external industrial processes.

### 13.3.1 Cooling Water Systems

Various process wastewaters can be utilised as make up to replace evaporative losses from wet cooling systems. The suitability of a wastewater for reuse in cooling water systems is dependent largely on the characteristics of the effluent stream, particularly the tendency of the wastewater for scaling, fouling and corrosion. The tendency for corrosion must be considered to ensure compatibility with system metallurgy. The design and operation of cooling water systems may not permit the reuse of some waters.

### 13.3.2 Demineralised Water Treatment Plant

High quality wastewaters, such as boiler blowdown and condensates, can be recycled to the demineralised water treatment plant for boiler make up water production. These types of water are often of a higher quality than the demineralisation plant raw water supply and reuse can present cost savings due to both reduced raw water abstraction and reduced treatment requirements. Temperature reduction of boiler blowdown is required before reuse is practicable. In modern power plant, this is achieved generally by mixing the blowdown with quench water. As the quench water employed is often from a town's main supply or sea water, this impacts upon the quality of the final blowdown stream.

### 13.3.3 Flue Gas Desulphurisation Processes

Wet flue gas desulphurisation (FGD) systems are major water consumers in the water balance of coal-fired plant. Most water is lost through evaporation with the exiting flue gas, whilst a smaller volume is lost with the dewatered solids. FGD equipment is already designed to handle liquid streams that are high in dissolved salt content and precipitated gypsum solids. Therefore, low quality waters can generally be used as make up water for FGD systems without affecting plant performance. In the UK, make up water for FGD plant is generally abstracted from the cooling water system.

Depending on quality, make up water can be introduced into the FGD system in a variety of areas, including mist eliminator wash, reagent preparation and feed system, gypsum wash water and pump and equipment seal flushing. However, each of these areas may require different levels of water quality with respect to dissolved and suspended solids. In the limestone gypsum process, careful consideration needs to be given to the effects of recycling wastewaters containing high concentrations of chloride salts on purge flows from the absorber, and to the potential impact of impurities contained in the make up water on produced gypsum quality.

### 13.3.4 Coal and Ash Handling

Coal and ash handling processes can tolerate low quality wastewaters containing relatively high levels of suspended and dissolved solids. These processes require large quantities of water for dust suppression and equipment washes. Substantial volumes of water can also be required for ash sluice systems and fly ash transport, although this is dependent on the specific waste handling process employed. Wastewater from furnace

bottom ash transport can also be reduced by the use of a closed-loop recirculating system.

### 13.3.5 Equipment Washes

Raw water consumption can be reduced by using low quality wastewaters for maintenance and cleaning activities, such as air pre-heater washes and equipment washes in the FGD system and coal handling areas.

### 13.3.6 Reuse of Industrial Wastewaters

Various wastewaters from external industrial processes can be utilised as make up water for power plant water consuming processes if power plant and industry are located adjacently. Most such schemes involve power plant wet cooling tower systems, which are generally the largest water consuming processes at sites. For significant power plant dependence on industrial wastewaters, this clearly requires long term guarantee of supply.

Secondary or tertiary treated effluent from municipal sewage plants is a viable source for cooling tower make up due to the relatively large volumes obtainable. Wastewater from municipal sewage plants, known as either reclaimed water or grey water, has been used in power plant cooling systems for many years. Reclaimed waters characteristically contain high concentrations of organic matter, ammonia, phosphorous and bacterial growths. This has resulted in biological fouling, deposition, corrosion and scale formation in a number of cooling water applications where circuit chemistry has not been controlled adequately.

Wastewater from power plant processes can also be reused externally in industrial processes. Examples in the literature include water discharged from power plant cooling water systems being used as feedwater for external industrial processes, desalination and potable water production, and in agricultural irrigation schemes. For example, at Gregory power plant in the USA, municipal wastewater is filtered and used as cooling tower make up. Blowdown from the cooling water system is then used as feedwater for a local alumina processing plant where there is no requirement for high purity water.

## 13.4 Reduced and Zero Liquid Discharge Systems

### 13.4.1 Introduction

By definition, reduced or zero liquid discharge (ZLD) processes treat significant volumes of low quality wastewater, such that the waste stream is greatly reduced, or eliminated, and the bulk of the wastewater becomes reusable. The minimisation of blowdown from wet cooling tower systems is a key part of any ZLD process, as this is generally the largest wastewater discharge at a facility.

In ZLD applications, a number of different plant wastewater streams may be combined for processing. The initial stage in the treatment process usually involves volume reduction, as there are economic benefits in minimising the final waste stream for disposal. Reuse of the concentrated effluent is rarely practicable and a final treatment

stage is usually required to convert the remaining dissolved solids to a suitable medium for disposal, most commonly to a solid product for landfill.

The capital and operating costs of ZLD processes are usually substantial. ZLD applications frequently utilise a number of treatment stages and may require highly alloyed materials of construction for corrosion resistance, entailing high capital costs. Operating costs for ZLD technologies are often significant due to high energy consumption and chemical usage, and the disposal costs of waste sludges and solids.

Processes that have been used for ZLD systems and cooling tower blowdown treatment, individually or in combination, include the following:

- Evaporation basins;
- Brine concentrators;
- Crystallisers;
- Membrane processes.

A brief description and summary of relevant operational experience for each of these technologies is presented below [3]. The main advantages and disadvantages of the most frequently utilised processes are highlighted in Table 13.2.



Process	Advantages	Disadvantages
Evaporation Basins	Passive process Low operating cost Operating flexibility	Large space requirement May be cost prohibitive Geographical limitations Environmental impact Public perception
Brine Concentrator	Proven performance Reliable operation Multiple suppliers High concentrations Reusable distillate	High capital cost High energy cost Long lead time Costly redundancy Construction schedule Aesthetics
Crystalliser	Multiple suppliers Steam driven option Reusable distillate	High capital cost Foaming potential Long lead time No redundancy High maintenance Solids disposal
Membrane Process (with pre-treatment)	Built-in redundancy Low capital cost Low energy cost Reusable permeate	Complex process Multiple chemicals Reliability Susceptible to upsets

**Table 13.2: Zero Liquid Discharge Process Advantages and Disadvantages**

### 13.4.2 Technologies

#### Evaporation Ponds

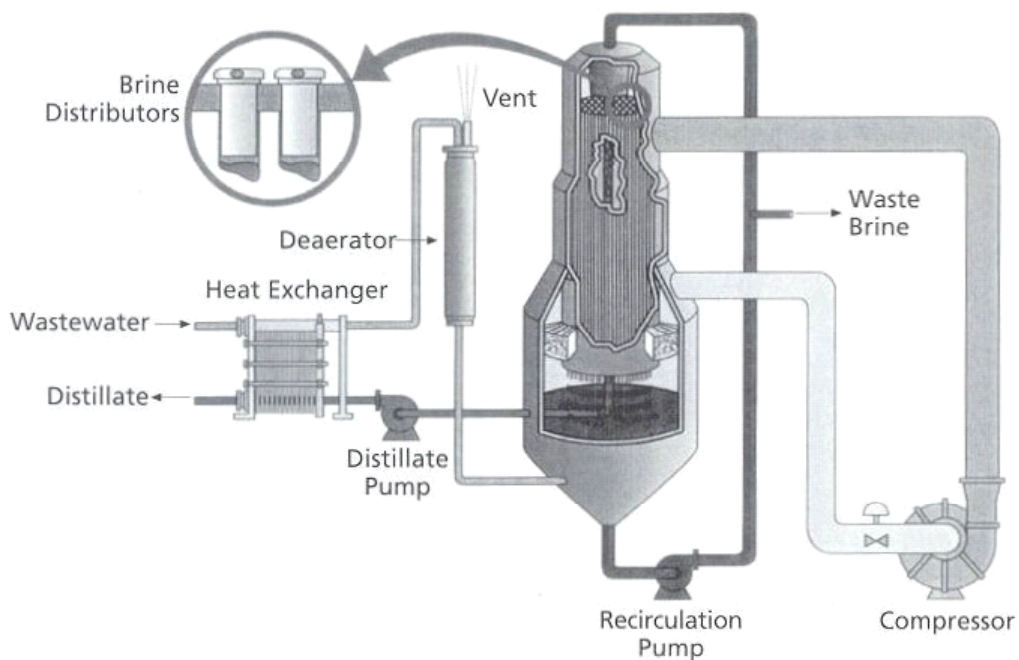
Evaporation ponds or basins can provide a simple, flexible and relatively low operating cost method for wastewater disposal. Ponds are relatively shallow to maximise surface area and designs typically include a system of liners with leak detection to protect ground water supplies. However, evaporation ponds are only suitable for plants located in arid regions, where solar evaporation significantly exceeds annual rainfall. Evaporation ponds are not practical options for most plant due to the climate at a given location or restrictions on available land space.

#### Brine Evaporators/Concentrators

Brine concentrators have been used extensively for wastewater volume reduction at power plant, with over 100 installations used in zero liquid discharge systems. Brine concentrators are capable of recovering greater than 95% of a wastewater flow as high purity distillate (< 10ppm TDS). The distillate is generally reused as either cooling tower make up or as feedwater for demineralisation plant. The concentrated brine slurry produced (> 150,000ppm TDS) can be reduced to dry solids in a crystalliser or spray drier, or sent to an evaporation pond.

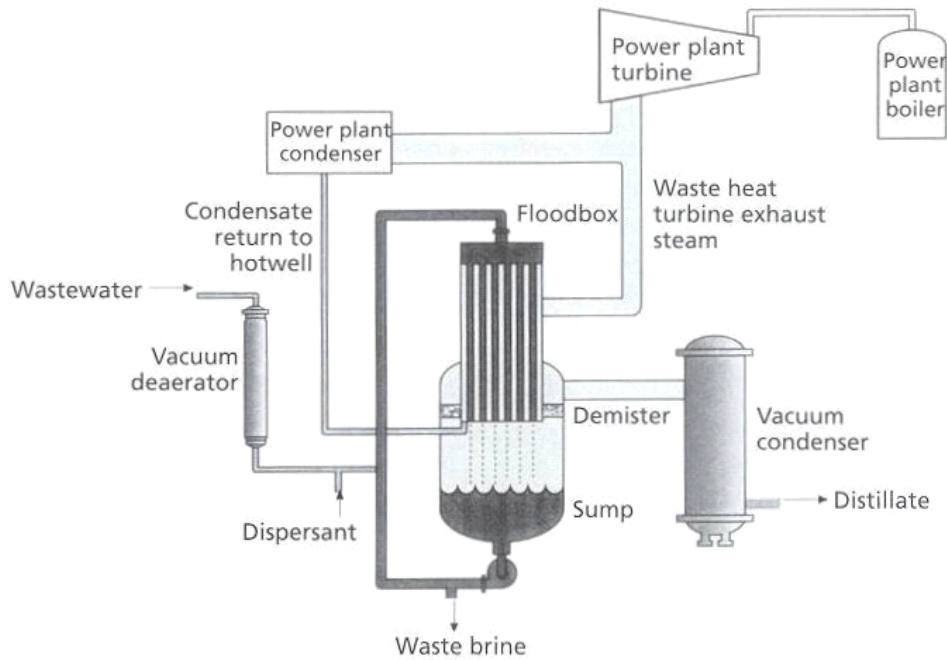
The brine concentration process utilises a vertical falling film evaporator with vapour recompression cycle and calcium sulphate seeding of the brine to control scaling (Figure 13.1) [4]. Feedwater pre-treatment consists typically of filtration, acid injection and deaeration for the control of scaling and corrosion. The deaerated feedwater is fed to the evaporator sump for combination with circulating brine slurry. The brine slurry is

continuously circulated from the sump to a flood box at the top of the heat transfer tubes, from where it is distributed and falls by gravity as a thin film down the inside of the tubes. As the brine falls back into the sump, a small portion is evaporated and drawn through mist eliminators to a compressor. The compressed vapour then flows over the outer tube surfaces, where heat is transferred to the cooler brine within the tubes. This causes a small amount of internally circulating brine to evaporate and condenses the external vapour as distilled water. The distillate is pumped back through a heat exchanger to pre-heat the incoming wastewater. To control evaporator slurry density, a small amount of the concentrated brine is continuously blown down for further processing or disposal.



**Figure 13.1 : Vapour Compression Brine Concentrator System  
(Courtesy of Ionics, Inc)**

Power plant turbine exhaust steam can also be used to evaporate wastewater in waste steam brine concentrators (Figure 13.2). These tap directly into the steam line between the power plant and its condenser, or into the condenser steam shell. By operating under vacuum and by using a proprietary configuration, wastewater can be evaporated at very low temperature (40 to 50°C), greatly reducing the risk of corrosion and reducing energy requirements.



**Figure 13.2 : Waste Steam Brine Concentrator (Courtesy of Ionics, Inc)**

The disadvantages of brine concentrators are largely economic, as they entail substantial capital and operating costs. High capital costs result from the use of titanium or stainless steel alloys for heat exchanger surfaces, which are necessary to tolerate the extremely corrosive conditions experienced when treating saline wastewaters. Brine concentrators consume large amounts of electricity, typically between 80 to 100kWh per 1000USgallons of wastewater treated, resulting in significant operating costs. To minimise the size of brine concentrator required, reverse osmosis is used frequently for wastewater volume reduction beforehand.

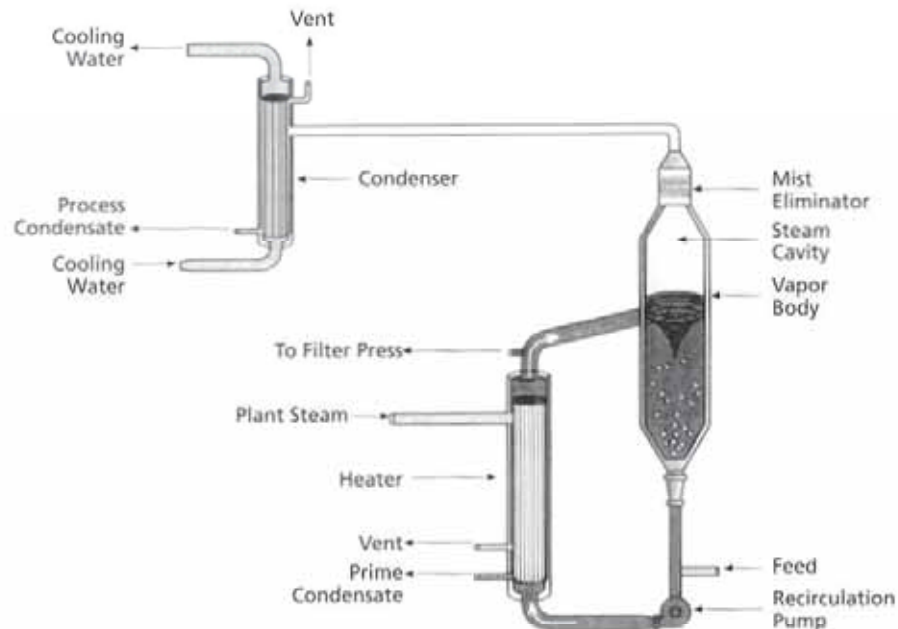
Brine concentrators are reported to operate very reliably, particularly when run in steady state mode. Problems that have been experienced are usually the result of scale build up, which necessitates periodic outages for mechanical cleaning, high pressure water washing and chemical cleans. Stress corrosion cracking of stainless steel materials has been an issue at some plants and there are other examples in the literature of general corrosion [5, 6].

### Crystallisers

Crystallisers are used to reduce the brine concentrate from volume reduction processes (such as brine concentrators and membrane processes) to a dry solid product.

Crystallisers are thermal evaporators that can be driven by either steam or mechanical vapour compression (Figure 13.3) [4]. Slurry from the volume reduction process is sent to the crystalliser sump and then to a flooded shell and tube heat exchanger. Because the tubes are flooded, the brine is under pressure and does not boil, thus preventing scaling. The brine enters the crystalliser vapour body at an angle and is swirled into a vortex. A small amount of the vapour evaporates and crystals form. Most of the brine is

recirculated back to the heater. A small stream is removed for solids dewatering, usually using a filter press or centrifuge. The dewatered product is sent normally to a landfill site, but can be commercially saleable. Distillate recovered during the process is suitable for reuse in high quality water applications.



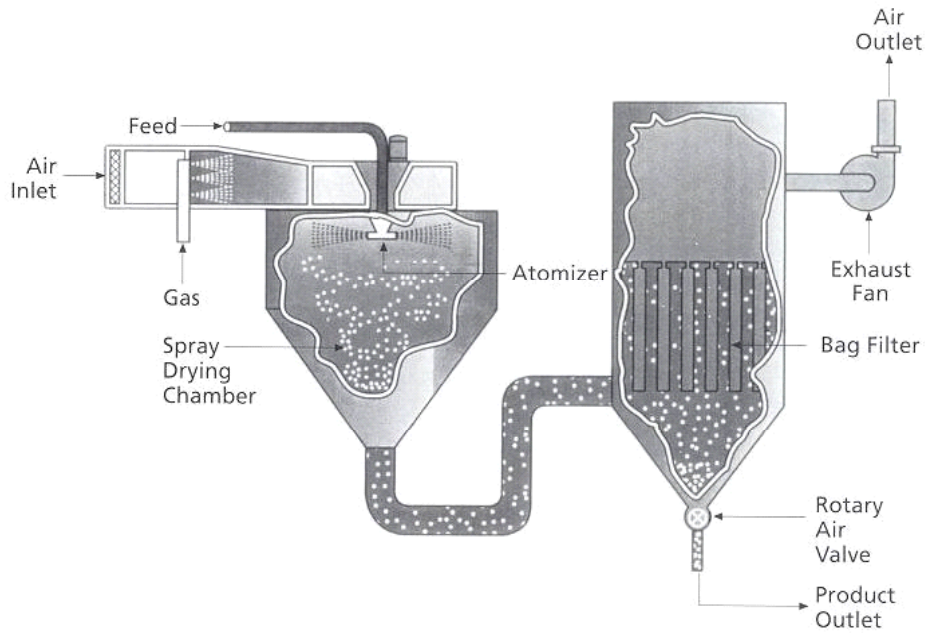
**Figure 13.3 : Forced Circulation Steam-Driven Crystalliser (Courtesy of Ionics, Inc)**

The use of steam for heating simplifies the design and operation of the crystalliser, but does result in significant steam and cooling water requirements for a utility plant item. Vapour recompression crystallisers eliminate steam and cooling water requirements, but add electrical demand and are very susceptible to operational upsets, such as foaming. Crystallisers require highly alloyed materials, which again incurs a high capital cost.

### Spray Driers

Spray driers are alternatives to crystallisers for reducing concentrated brine solutions to solids for disposal. The spray drier consists of an atomising wheel spinning at approximately 17,000rpm that sprays the brine slurry into a hot, gas-filled chamber (Figure 13.4) [4]. Water instantly evaporates from the brine droplets and the solids are drawn into bag filters.

Problems have been reported with the longevity of stainless steel wheels due to the corrosive and erosive nature of the brine slurry. A double-disk, ceramic lined, titanium wheel is reported to have worked well, with a lifetime of approximately three years [5].



**Figure 13.4: Spray Dryer (Courtesy of Ionics, Inc)**

## Membrane Techniques

Reverse osmosis (RO) has been used for wastewater volume reduction in a number of ZLD applications. RO is generally the least costly method of wastewater volume reduction and can be used to concentrate wastewaters containing high levels of dissolved salts, silica and organic matter. Water recoveries of approximately 75% are quoted typically when used to treat power plant wastewaters.

In reverse osmosis water reuse applications, the purified permeate water is of suitable quality for reuse in most plant areas. The concentrated reject stream is either processed further, for example in a brine concentrator and/or crystalliser, or reused in low quality water applications.

In wastewater treatment processes, RO membranes can be particularly susceptible to scaling and fouling and regular membrane cleaning can often be necessary. The key issue for successful RO plant operation is correct feedwater pre-treatment, since wastewater streams can often be near saturation for several constituents and can also contain relatively high concentrations of suspended solids. RO pre-treatment typically consists of lime softening and filtration in wastewater applications. However, membrane fouling has resulted frequently from poor softener/clarifier performance, often as a result of suspended solids carryover. Microfiltration (MF) and ultrafiltration (UF) are increasingly being used for the removal of suspended solids and biological matter from wastewaters before RO systems.

High Efficiency Reverse Osmosis (HERO) has been used in several wastewater treatment applications [7]. Membrane operation at high pH is reported to confer a number of advantages in comparison to convention RO systems that run at a near neutral or slightly acidic pH (6.5 – 7.0). These include greater rejection of weakly

ionised species, higher permeate recovery rates ( $\geq 90\%$ ) and prevention of biological fouling. As with conventional RO, pre-treatment is critical for successful operation.

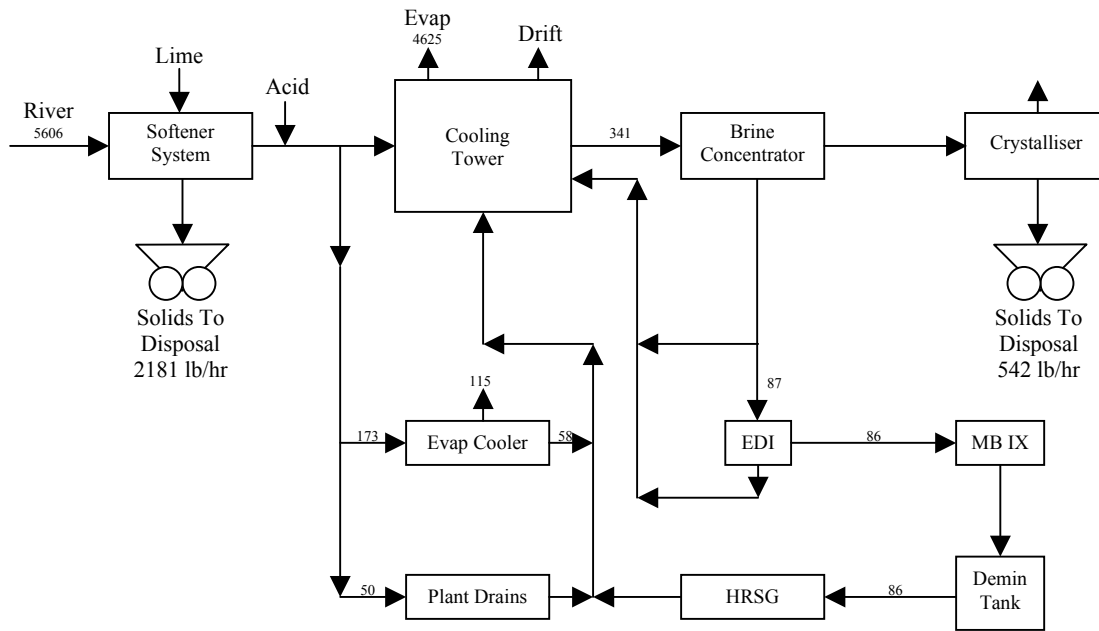
Electrodialysis (EDI) and electrodialysis reversal (EDR) can be used in final polishing applications, but require a relatively high quality feedwater. Neither process can tolerate high levels of silica or organics. Of the two processes, EDI is the more commonly used at present.

#### Case Study – Guadalupe Zero Liquid Discharge Power Plant

Guadalupe power station is a 1000MW CCGT plant located in Texas, USA [2]. Guadalupe has a fully integrated zero liquid discharge water/wastewater treatment system for optimisation of the site water balance. Plant commissioning commenced in 2000 and the site was handed over for commercial operation in 2001. The site water balance is shown in Figure 13.5 below.

Raw water from the nearby Guadalupe River is abstracted for use as make up water to the wet tower cooling system. The river water is pre-treated firstly in a softener/clarifier to reduce the levels of calcium and silica in the make up, which allows the cooling system to operate at concentration factors of up to 12. The clarifier also removes suspended solids, which are particularly prevalent in the river water during periods of heavy rainfall. The softener sludge is thickened and dewatered in a filter press for off-site disposal.

The cooling tower blowdown is sent to a mechanical vapour recompression brine concentrator, where 99% of the wastewater is recovered as high quality distillate (5 – 10ppm TDS). The blowdown from the brine concentrator is fed to a steam-driven crystalliser. The bleed flow from the crystalliser goes to a pressure filter for final dewatering, which reduces the waste stream to solids for off-site disposal. A portion of the distillate from the brine concentrator is directed to an electrodeionisation unit, which provides the plant's demineralised boiler make up water. The remaining distillate is recycled to the cooling tower. An ion exchange mixed bed was provided as back up for the electrodeionisation.



**Figure 13.5 : Guadalupe CCGT Power Station (Texas, USA) – Site Water Balance [all flows in USgpm except solids] (Courtesy of Ionics, Inc)**

### 13.5 References

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## **14 WORLD-WIDE ACTIVITIES**

### **14.1 Introduction**

This chapter reviews developments in the global water treatment market and the capabilities of the key players for fossil fuel based power plant applications. The main focus in this report is on the major product manufacturers and integrators that are active in the global market, primarily original equipment manufacturers (OEMs), ion exchange resin manufacturers, membrane manufacturers and contract operating service providers.

It is acknowledged that the water treatment market for power plant consists of a number of different sectors and types of companies. Whilst there are a wide range of businesses that are also active within the industry other than those listed above, these are not discussed further within the scope of this review. This excludes specialty chemical producers, providers of monitoring instrumentation, analytical laboratories and engineers and consultants.

Three approaches were taken to finding information for this section of the report.

1. An internet search was carried out in order to identify the main companies that are active in the field. Appendix C shows a list of the companies identified and a summary of their capabilities. A brief questionnaire was sent to each of these, but only seven complete responses were received.
2. A survey of published information was undertaken, including a review of journals and market research reports available. These provide a general overview of industrial water treatment trends and developments, but with limited specific detail regarding the power industry.
3. External consultations were held with various water treatment plant suppliers to gain views on developments in the market place.

### **14.2 Survey responses**

The capabilities of the companies that responded to the survey are summarised in Table 14.1 below.

Company		ACWa Services Ltd	Alpheus Environmental Ltd	Aquatech International Corp.	Christ Kennicott Water Technology Ltd	Hydranautics	Ionpure Technologies	Memcor Ltd
<b>Applications</b>	Boiler make-up	X	X	X	X	X	X	X
	Condensate polishing	X		X	X			
	FGD wastewater treatment plant	X		X				
	Cooling water treatment			X	X			
	Water re-use schemes / Zero liquid discharge	X	X	X		X		X
<b>Capabilities</b>	Consultant			X				
	Design	X		X	X			X
	Manufacture	X		X	X	X	X	X
	Commission	X		X	X			X
	Operate		X	X				
	Maintenance		X	X	X			X
	Outsourcing		X	X				
<b>Technologies</b>	Reverse osmosis	X	X	X	X	X		X
	Microfiltration	X	X	X		X		X
	Ultrafiltration	X			X	X		
	Nanofiltration	X				X		
	Membrane desalination	X		X	X	X		
	Thermal desalination			X				
	Electrodeionisation			X	X		X	
	Conventional ion exchange	X		X	X			
	Clarifiers	X		X				
	Media filters	X		X	X			
	Evaporators and crystallisers			X				

**Table 14.1: Summary of Capabilities of Companies Responding to Survey**

## **14.3 The Global Power Plant Water Treatment Market**

### **14.3.1 Market Potential**

The power generation industry is predicted to remain a very significant industrial market for water treatment equipment and associated supplies. Growth for water treatment products in the power industry is expected to be typical of overall average growth in industrial water treatment markets.

Estimates of the potential market for water treatment products in the power industry were obtained from market research reports. However, market estimates could range widely between studies, often depending on definitional differences and assumptions.

In one study, demand for water treatment products for power plant applications worldwide is projected to increase 6.7% per year, from \$4.4 billion in 2004 to \$5.4 billion in 2007 [1]. Most of this market is associated with conventional power plant water treatment processes such as physical filtration, clarification and chemical conditioning.

By comparison, the power industry market for ultrapure water systems utilising advanced water treatment technologies (membrane filtration, ion exchange, electrodeionisation, ozone and ultraviolet light) was estimated to be worth around \$700 million worldwide during 2004 [2]. Another study estimated that the US market alone for advanced water treatment for power producers was worth \$487 million in 2003, with sales projected to increase at an average annual rate of 8.3% to reach \$726 million by 2008 [3].

### **14.3.2 The Chinese Market**

China represents a huge market for water treatment products and services, but is viewed as a difficult place to do business. Rapid industrialisation and urbanisation has meant that lack of water availability has become a limiting factor to future growth in certain areas and industries due to uneven geographical distribution of supplies, over-consumption and declining groundwater resources and polluted waterways throughout the country. In municipal and industrial applications, water reuse and desalination is essential to China's sustainable development. This has resulted in high growth rates predicted for membrane equipment, which has attracted some of the world's largest companies to the region.

In the power industry, large projects involving overseas membrane suppliers have already been completed, or are in progress [4]. ZENON recently completed \$6 million worth of industrial wastewater treatment contracts, where the effluent is reused for boiler feed water or cooling tower make up. Norit/X-Flow have been involved in collaborations with a local firm in power plant projects treating wastewater and cooling water and in other power plant water recycling projects.

Most overseas companies operating successfully within the Chinese market have done so through maintaining an active local presence, establishing subsidiaries and manufacturing facilities in China or neighbouring Asian nations, or developing partnerships and licensing arrangements with local companies. Companies manufacturing outside of China can no longer compete on a cost basis for technologies

where there is an indigenous capability. However, the lack of intellectual property protection has made many overseas firms wary of entering the Chinese market.

Strong local players are emerging in the market, both as water treatment plant equipment fabricators and developers in their own right, and as product distributors for overseas companies in the Chinese market. In the long-term, increasing competition for power plant water treatment contracts worldwide is expected to come from Chinese firms. At present, there is generally little interest from Chinese firms in exporting equipment due to the size of the indigenous market.

#### **14.4 Suppliers of Water Treatment Equipment**

##### **14.4.1 Market Consolidation**

Over the past decade, major industrial corporations have moved to re-position themselves strategically in order to take advantage of developing opportunities in the water and wastewater treatment industry. The water and wastewater treatment industry has now become a major global business and many factors are expected to drive significant growth in the market. Estimates of the world market for water and waste treatment technologies vary from \$360 to \$655 billion at present [5]. This includes annual sales of equipment and services related to water/wastewater, air pollution, solid and hazardous waste, recycling and remediation. Huge capital expenditure in infrastructure is required over the coming decades to address growing problems with water availability and quality and to ensure compliance with increasingly stringent regulatory controls and enforcement. Desalination and water reuse are seen as particular growth areas. In order to become significant players in the water treatment and purifications business, major industrial corporations have assumed control of many of the foremost companies and assets in the treatment sector [6]. This has resulted in significant rearrangement of ownership and increasing consolidation amongst water and wastewater treatment companies. Of particular note is the emergence of General Electric and Siemens as new diversified water companies and major players in the water treatment equipment industry.

For the large technology companies, global presence is now a critical element for success. Most successful water treatment vendors now have a local presence in different countries in order to enable a greater understanding of regional business customs and requirements, as well as to provide enhanced service and support capabilities. This has generally been achieved through strategic acquisitions of distribution and technology companies, as well as through entering into partnerships and licensing agreements with firms that have strong positions in their respective local markets.

In the power industry, further consolidation of the water treatment market has been driven by the major combustion turbine OEMs expanding their offering to fuel and water handling systems in recent years, partly to offset turbine sales decline, but also to provide more reliable sources of revenue through service contracts and overall engineering [7].

#### 14.4.2 Profiles of Main Water Treatment Equipment Suppliers

The major companies of particular relevance for power plant water treatment applications in Europe are profiled briefly below.

##### GE Infrastructure Water and Process Technologies

Water and Process Technologies is a part of GE Infrastructure, one of GE's primary businesses.

GE has emerged as one of the leading original equipment manufacturers and service providers of water purification and treatment technologies worldwide through a number of acquisitions in recent years. In May 2004, GE Infrastructure Water and Process Technologies was formed through the integration of GE Betz, GE Osmonics and GE Water (previously Glegg Water Conditioning). In January 2005, this was followed by the acquisition of Ionics Inc. in a transaction valued at \$1.1 billion, plus the assumption of existing debt. Ionics itself is a global leader in membrane and other water treatment technologies and had previously acquired Ecolochem Inc., a provider of emergency and mobile water-treatment services to the power, petrochemical and other industries, for approximately for \$338 million in cash and stock in January 2004. Cumulatively, GE has gained approximately \$2 billion worth of water revenue through the fore mentioned acquisitions at total costs of around \$3.5 billion [8]. GE has also signed a contract with Pall Corporation for the integration of Pall's microfiltration and ultrafiltration technologies with GE's reverse osmosis systems.

The acquisition of Ionics established GE as a key player in the world water business. GE is now one of the largest companies in the North American water treatment plant business and a leader in the desalination and water reuse segment for municipal and industrial customers. The European market is serviced through local engineering facilities in a number of countries, with design and manufacturing undertaken at factories in Italy and Spain.

##### Siemens (USFilter)

In July 2004, Siemens completed the acquisition of the product, systems and services businesses of USFilter Corporation from Veolia Environnement for \$993 million. The USFilter businesses have been added to Siemens' \$4 billion Industrial Solution and Service (I&S) group as a new 'Water Technologies' division. Annual revenues for USFilter are given as \$1.2 billion [9].

The acquisition of USFilter positions Siemens as a market leader in the municipal and industrial water and wastewater treatment industry in North America and with greater presence in all segments of the water industry. Siemens is one of the world's largest infrastructure service companies, with a presence in around 190 countries. USFilter operations are themselves extensive, with 157 locations worldwide. This is likely to provide opportunities both for cross-selling amongst existing Siemens and USFilter companies and, additionally, for expanding USFilter into countries where Siemens already has a strong presence.

## Veolia Water

Veolia Water, a unit of Veolia Environnement (previously Vivendi Environnement), provides water and wastewater services worldwide, with a revenue of €11.3 billion in 2003.

Veolia Water Systems is the engineering, design and build subsidiary of Veolia Water, with an estimated revenue of €1.3 billion in 2004. Subsidiary companies in over 50 countries provide local customer support networks. Capabilities include pure and ultra-pure water systems, industrial effluent treatment, water chemical treatment and mobile treatment plant. In September 2003, Veolia Water Systems relaunched its purified water treatment activities under the brand of Elga Process Water. Other principal subsidiaries include OTV and Krüger.

During 2003, Veolia Water continued its divestment of non-strategic activities, mainly in the United States, and intensified its strategic refocusing on its water and waste water management services for local authorities and industrial clients.

## SUEZ Environnement (Ondeo Industrial Solutions)

SUEZ Environnement, a SUEZ business line, is one of the world's water and waste service sector leaders. Ondeo, Degrémont and SITA are the three commercial trade names representing SUEZ Environnement's activities.

Ondeo Industrial Solutions provides process and management improvements for the industrial water cycle, having assumed the industrial water and wastewater capabilities of Degrémont in approximately 2001. Capabilities for water treatment plant include outsourcing, design and construction, turnkey solutions and supply of chemical products. Ondeo IS had a turnover of €168 million in 2003 and operates and maintains over 200 industrial water treatment plants around the world.

Degrémont now designs and constructs drinking water production or desalination facilities, waste water treatment plants and sludge treatment facilities for local authorities

## Christ Water Technology Group

The Christ Water Technology Group provides water treatment solutions in process plant construction and in the services sector in the field of pure and ultrapure water production, drinking water production and the treatment of wastewater and sewage. In 2004, total sales amounted to €173.2 million. The Christ Water Technology Group is a business unit of the BWT Best Water Technology Group.

The Christ Power Generation Business Unit provides water treatment systems for industrial and utility scale power plant applications worldwide, including plant for boiler feed water, condensate polishing and cooling water and wastewater treatment.

Companies active in the field of power generation within the Christ Group include:

- Christ AG (Switzerland);

- Christ Kennicott Water Technology Limited (UK);
- Christ BV (Netherlands);
- Tepro Project Engineering Wassertechnik Ges.m.b.H. (Austria).

The Christ Group is active in markets in Western and Eastern Europe, the Near East and the People's Republic of China. Customers have included ABB, Alstom, E.ON, Lurgi, Mitsubishi Heavy Industries, Siemens and various power plant operators.

#### 14.4.3 Trends in Manufacturing

Original equipment manufacturers are increasingly undertaking procurement on a global basis to achieve the lowest cost supply for projects. This has resulted in increased outsourcing of plant component build to companies in China, India, other Southeast Asian countries and Eastern Europe to take advantage of low manufacturing costs. Similarly, amongst most major equipment and product companies, there has been a trend of relocating manufacturing facilities to East Asia and Eastern Europe, instead of manufacturing within Western Europe and the United States.

Although there are regional differences in customer expectations of quality from low cost component build, quality of manufacture can be a particular problem for items produced in factories within East Asia at present. In the power industry, the use of such products in water treatment plant can frequently result in subsequent problems with plant operation and availability. In new build projects, this can result in demineralised water unavailability for activities such as steam blows and reliability runs. This in turn can result in significant delays in overall power plant commissioning programmes, incurring substantial financial penalties for EPC contractors consequently.

#### 14.4.4 Contract Award by Electronic Auction

Electronic auction (e-auction) is used increasingly by companies for the procurement of goods and services at the lowest possible capital cost. In e-auctions, selected suppliers are invited to place bids and the price is reduced with each bid placed. The supplier with the lowest bid wins the auction and is awarded the contract.

In the power industry, large EPC contractors and industrial companies, including Siemens, Alstom and Shell, have already put significant investment behind processes to facilitate e-auctions. Although clients can use a weighted system to take into account benefits, risks and preference for each vendor, there are concerns for industrial projects that the bidding process does not allow sufficient differentiation between capital costs, technologies offered or quality of engineering. However, e-auction is expected to become an increasing trend with which suppliers will need to become familiar with.

### 14.5 Trends in Technologies

The potential for future developments in water treatment technologies was reviewed in Section 12.0. Other market influences that may affect the application of selected technologies in power plant are highlighted below. Leading manufacturers are also listed.

### 14.5.1 Ion Exchange

Ion exchange remains a viable option as a full scale demineralisation process for many power plant water supplies where water quality is suitable for application.

Ion exchange is generally viewed as a more robust and reliable option than membrane technologies at present. This is an important consideration for water treatment at power stations, where there is a general trend of reducing manpower and technical expertise at sites.

Ion exchange will always be limited by the need for regenerant chemicals and the production of a chemical waste stream. This can restrict application due at power plant due to site safety or environmental requirements, unless resin regeneration can be undertaken off-site, e.g. through the use of mobile water treatment plant.

The main global suppliers of ion exchange resins are Dow, Lanxess, Purolite and Rohm and Haas.

### 14.5.2 Membrane Processes

There has been rapid and significant growth in demand for membranes due to the increasing need to treat low quality water supplies. Improvements in membrane systems are expected to continue, driven primarily by the municipal water and waste water treatment market

At power plant, membranes are expected to see greater application as growing pressures on clean water availability require increased the use of alternative water sources in plant processes.

#### Reverse Osmosis

The global market for reverse osmosis membrane modules in the water industry was estimated to be \$400 million in 2004 [10]. Of the membrane suppliers, Hydranautics possesses the largest amount of installed capacity, followed by DuPont, Dow, Toray and Koch Membrane Systems

Reverse osmosis has been used at power plant for many years to reduce chemical consumption and operating costs associated with traditional ion exchange demineralisation plant. However, membrane systems still have issues of acceptance within the power plant market due to on-going concerns regarding reliability of operation, stigma attached from less successful early experiences and the risk averse nature of the power industry.

Reverse osmosis systems require frequent monitoring and maintenance for satisfactory operation. Reliability is a key concern for power plant where there has been an increasing trend of reducing manpower at sites.



## Microfiltration and Ultrafiltration

Microfiltration and ultrafiltration membranes are expected to see significant future growth in the world market for water and wastewater filtration equipment. This is likely to be mainly in reverse osmosis pre-treatment applications in the municipal water and wastewater treatment industry.

Worldwide sales of microfiltration and ultrafiltration membranes were estimated at \$300 million in 2001 and are projected to grow to \$11.9 billion by 2010 [11]. Leading suppliers include Memcor, Norit, Pall/Asahi and ZENON.

In general, microfiltration is preferred to ultrafiltration at present due to advantages of greater reliability and durability in operation. Microfiltration is generally considered to be sufficient for reverse osmosis pre-treatment without the need for ultrafiltration. In practice, there can be some difficulty in differentiating between the two technologies, depending on how suppliers have defined pore size.

Both microfiltration and ultrafiltration are becoming more attractive options to conventional depth filters where suspended solids levels are suitable for application. Microfiltration and ultrafiltration are also capable of producing treated water of higher quality by comparison.

## Electrodeionisation

Electrodeionisation (EDI) is an increasingly viable economic and environmental alternative to mixed bed polishing as a chemical free technology in demineralisation systems. Most applications to date have been driven by environmental considerations.

Despite advances in design and materials and continued reduction in capital costs, adoption of EDI by the power industry has been slow, again due to the risk averse nature of the industry. Wider acceptance is not considered likely until successful operating experience in larger scale applications has been gained and promulgated.

## **14.6 Water Treatment Outsourcing**

The power industry has been a leading market for the outsourcing of water treatment systems to third party service providers and further growth is expected. Whilst water treatment outsourcing has been used historically to provide emergency or short-term water treatment facilities at power plant, long-term outsourcing agreements can be an attractive alternative for power plant owners when compared to capital investment in permanent equipment. Outsourcing water treatment can be a viable economic option for new build power plant, as well as for stations with limited remaining operation life. Outsourcing also presents a low risk option for site water treatment and places minimal resource demand on power plant personnel. Factors that have promoted or held back outsourcing are summarised in Table 14.2 below.

Drivers	Restraints
<ul style="list-style-type: none"> <li>• Capital cost savings</li> <li>• Operational cost savings and efficiency benefits</li> <li>• Fixed costs and predictability</li> <li>• Regulatory pressures to reduce waste water discharge by eliminating on-site regeneration and chemical storage</li> <li>• Staff reduction and loss of technical expertise at sites</li> <li>• Transfer of operational and performance risk</li> <li>• Consistent treated water quality</li> </ul>	<ul style="list-style-type: none"> <li>• Perceived risk</li> <li>• Lack of competitiveness</li> <li>• Poor asset inventory</li> <li>• Complex negotiations</li> <li>• Long pay back period</li> <li>• Economic instability</li> <li>• Self sufficiency</li> </ul>

**Table 14.2: Factors Influencing Outsourcing of Industrial Water Treatment**

A variety of outsourcing contracts can now be placed with vendors [12]. These can range from build, own, operate and maintain (BOOM) agreements, to contracts that may only cover part of a water treatment system, or cover just plant operation and maintenance. The duration of service contracts can extend from a few months for emergency supplies, up to 10 to 15 years for permanent on-site systems. Service contracts can also be set up to include provision for seasonal power plant operation, potential variations in treated water quality or quantity requirements, or changes in treatment plant technologies to meet changing site requirements.

Outsourced system supply can include leased, portable or installed equipment. In general, equipment designs can be classified within four categories:

- Mobile trailer mounted demineralisation;
- Mobile trailer-mounted primary treatment (RO) and mobile demineralisation;
- Fixed primary treatment (RO) and mobile demineralisation;
- Fixed primary treatment (RO) and primary demineralisation and mobile polishing.

Mobile water treatment plant is generally used at sites with restrictions on chemical use or waste water discharge to allow off-site regeneration, as well as for emergency support. Fixed treatment systems eliminate issues associated with mobile plant, such as equipment preparation, delivery, set up time and charges.

## **14.7 Seawater Desalination and Power Plant Co-Location**

One of the main barriers for the wider implementation of seawater desalination for potable water production has been the cost of water treatment. In the Middle East, power generation remains relatively low cost and co-locating desalination plant and power plant can improve the economics of desalination. Co-location can also help to reduce the environmental impact of desalination plant effluent. Some of the common configurations of co-located power and desalination plant are outlined below.

### **14.7.1 Dual-Purpose Power and Water Plants**

Virtually all large seawater thermal desalination plant outside of the USA combine water production with the generation of electric power using the same fuel source. Efficient

power and desalinated water cogeneration depends upon an appropriate ratio of power-to-water production that matches regional demand, with consideration of seasonal fluctuations and types of power and desalination technologies used [13].

In the Middle East, the integration of CCGT and multi-stage flash (MSF) desalination processes has become a common and successful arrangement, by which overall costs are reduced through the effective use of thermal energy from the power plant in the desalination process. Plants of this type have been at the forefront of independent water and power projects in the region.

In dual-purpose water and power plant, most – if not all – of the steam raised in the HRSG is expanded in a back pressure steam turbine to around 3 bar (around 150°C) for use in thermal desalination. In MSF desalination, the steam is supplied to the brine heater of the MSF plant. Condensate from the brine heater is then returned to the power plant for reuse.

A limitation of the conventional MSF cycle is the high temperature of the brine heater condensate (113 – 115°C). This is much hotter than condensate returned to the HRSG in a normal CCGT cycle (35 – 40°C), which reduces power plant efficiency by comparison. A modified MSF cycle using a condensate cooler has been patented by PB Power to reduce the temperature of the condensate returned to the power cycle and improve power plant efficiency [14].

#### 14.7.2 Co-Location with Membrane Desalination Plants

Co-locating reverse osmosis membrane desalination plants with power plant can afford advantages of electricity supply, reduced costs of water production and reduced environmental impact of the desalination plant concentrate [15].

This approach includes the direct connection of the membrane desalination plant intake and discharge facilities to the discharge outfall of an adjacent once-through seawater cooled power plant. Cooling water discharged from the power plant condenser is typically 5 – 15°C higher than the temperature of the ambient ocean water. The use of this warmer water source as feedwater to the RO desalination plant lowers the feed pressure required for membrane separation by comparison to direct ocean abstraction, resulting in lower energy use and power costs for desalination.

By sharing a common discharge, the environmental impact of the desalination plant concentrate discharge is reduced as a result of mixing and blending of the membrane concentrate with the power plant cooling water system outflow. This also results in accelerated dissipation of both the salinity and thermal discharges. In general, there is a requirement for the power plant cooling water discharge flow to be at least three to four times larger than the desalination plant capacity. Additionally, the power plant outfall length has to be adequate to avoid the entrainment and recirculation of concentrate into the desalination plant intake.

#### 14.7.3 Hybrid (Thermal and Membrane) Cogeneration

Hybrid (thermal and membrane) desalination may offer additional flexibility to reach the optimum ration of power-to-water production. The heat from the power plant can be

used for thermal desalination, whilst electricity production can serve either large reverse osmosis units or vapour compression units.

#### **14.8 Worldwide FGD Activities**

As discussed in the DTI report 'Technology Status Review of Flue Gas Desulphurisation Technologies' in 2000 [16] the future market for FGD plant will be mostly, although not exclusively, associated with coal-fired power stations. This market can be divided into two classes; retrofits to existing power plant units and FGD equipment for new-build power plants. In general, the FGD retrofit market will be determined by tightening legislation in regions with an existing coal-fired generation capacity, whereas the market for FGD plant for new build power stations will be determined by the increase in coal fired generation capacity in regions with a rapidly increasing electricity demand, to be discussed in Section 14.

The DTI report 'Technology Status Review of Flue Gas Desulphurisation Technologies' concluded in 2000 that North America and China would dominate the future worldwide market for FGD. North America is expected to require mostly retrofitted FGD plant, whilst China would provide the greatest market for FGD plant on new-build power stations. Recent market analysis by Mcllvaine has confirmed this trend [17]. Mcllvaine report that of over 500 large FGD projects currently tabled for installation by 2012, China has the largest number already under construction and will continue to require the most new FGD systems over the next decade, whilst the US has the largest number of FGD plants currently in the planning stage. The opportunities for international FGD cooperation agreements and trade to introduce foreign equipment and technology into China are discussed in the IEA Clean Coal Centre report Coal in China [18]. Mcllvaine (2005) report that in Europe and the US the bulk of the FGD projects are retrofits to existing plant. In the US currently only one-third of the coal fired capacity has FGD installed and this will need to be substantially increased in light of the recently promulgated Clean Air Interstate Rule. In EU countries coal fired power plants effectively face limited operating hours and eventual closure by 2015 if FGD is not installed 1<sup>st</sup> January 2008 under the requirements of the revised Large Combustion Plant Directive (LCPD). In Asia new-build projects predominate, with Taiwan, South Korea and India expected to be relatively large purchasers alongside China, and even relatively poor countries such as Vietnam are reported to be undertaking new-build programs. It is predicted that more than 85% of these projects will employ the limestone or lime – gypsum process, with the majority of the remainder using lime in semi-dry or dry processes. A few projects are expected to use the ammonia process to produce saleable fertiliser.

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## **15 POWER MARKET SURVEY**

This chapter discusses the potential of various markets for fossil-fuel based power generation worldwide. This also provides an indicative assessment of the associated market for new water treatment plant. The views expressed are taken primarily from the EIA publication *International Energy Outlook 2004* and from internal consultations within E.ON UK, unless referenced otherwise [1].

### **15.1 Global Power Generation**

Global electricity demand is projected to increase by 2.3% per annum from 2001 to 2025. This will require the installation of nearly 5000GW of new generating capacity to meet the projected increase in demand and to replace ageing infrastructure. Total installed capacity is predicted to rise from 3397GW in 1999 to 7157GW by 2030 [2].

Much of the growth in new electricity demand is expected to come from developing Asia due to rapid economic growth in this region and, in some cases, population growth. Electricity use is expected to increase by 3.5% per annum in the developing world, compared with 1.6% per annum for industrialised nations.

Increases in future global electricity demand are expected to be met primarily through large scale (>30MW) fossil fuel based power plant. Whilst coal is projected to continue to retain the largest market share of electricity generation, natural gas fired generation is expected to become increasingly important. Gas is often preferred to coal in new thermal plants for its environmental advantages, lower capital costs and operational flexibility. Consequently, more new build gas plant is expected than coal plant. From 2000 to 2030, additional gas plant build of 2000GW is projected, mainly as large gas turbines (GTs), but with increasing application of micro, small and mid-size turbines. New build coal capacity of 1400GW is expected over the same period, mainly utilising Pulverised Fuel (PF) technology.

The actual future mix of power plant technologies in a particular country or region will be affected by a number of drivers, including [2]:

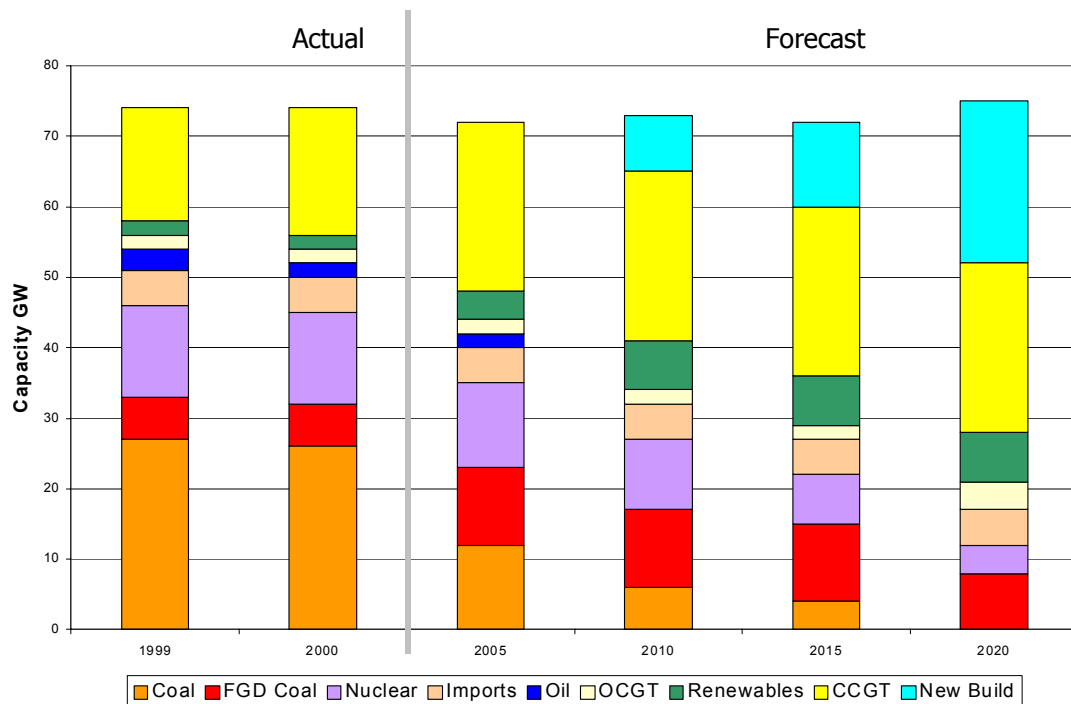
- Cost of plant (capital, through-life, fuel, infrastructure);
- Regulation (environmental, government policy, public opinion);
- Resources (fuel, fuel flexibility, security of supply);
- Business/market dynamics (deregulation, ownership, electricity/emissions trading).

Some of these drivers are expected to lead to growth in Distributed Generation (DG) plant, where electricity and heat is produced at or close to the point of consumption. Over the next 20 years, distributed generation plant could provide between 10 to 20% of global electricity production, with some displacement of conventional thermal power plant consequently.

## 15.2 UK Market

### 15.2.1 Overview

Over the next 10 to 20 years, considerable investment in UK generating capacity will be required. The introduction of carbon emissions trading in 2005 and the Large Combustion Plant Directive from 2008, combined with the retirement of most nuclear stations, could result in the need to replace almost half of the UK's power stations before 2016, with potential new build plant capacity of up to 20 to 25GW required (Figure 15.1).



**Figure 15.1: Potential Shortfall in UK Generating Capacity through to 2020**

In the short term, additional capacity is likely to be provided by the construction of new gas-fired plant and by the return of mothballed plant. However, regulatory uncertainty and unfavourable market conditions are holding back investment in new plant by power generators. The economic viability of new build gas plant is only marginal currently, mainly due to continued high gas prices in comparison to power prices.

### 15.2.2 Effects of Environmental Legislation

A series of European initiatives and Directives have been introduced recently, or will be introduced over the next five years, which are aimed at reducing pollution. These include:

- European Emissions Trading Scheme Directive, EU ETS (2005);
- Integrated Pollution Prevention and Control Directive, IPPC (2006 for the Electricity Supply Industry);
- Revised Large Combustion Plant Directive, LCPD (2008);

- National Emissions Ceiling Directive, NECD (2010).

For the power industry, the environmental regulations set out are intended to promote a move towards cleaner forms of power generation through incentives and limits on emissions. For fossil fuels, the standards being applied will tend to disadvantage coal in favour of gas because of the additional costs of emissions controls for coal plant by comparison and the possible long-term need to sequester some of the CO<sub>2</sub> formed.

The introduction of the EU carbon trading scheme and the Large Combustion Plant Directive have provided some incentive to invest in new CCGT plant, but uncertainty over the exact requirements of developing legislation has delayed investment. These directives are described briefly below.

- EU Emissions Trading Scheme

The EU carbon trading scheme is critical to EU efforts to comply with Kyoto protocol restrictions on greenhouse gas emissions by 2008-12. The trading scheme sets up a mandatory cap and trade CO<sub>2</sub> scheme for certain combustion installations and other industrial CO<sub>2</sub> sources. Carbon emission allowances are allocated to companies according to National Allocation Plans (NAPs). The first phase commenced in January 2005 and runs until 2007. The second phase runs from 2008-12 and is likely to involve stricter emission caps for market participants.

The scheme is likely to require the electricity industry to cut emissions, which would encourage a move away from coal-fired plant to gas and increase the pressure for new CCGT build. However, there is no legislation currently for the scheme beyond 2013. This has discouraged long-term investment in new power plant as the financial returns are uncertain.

- The Large Combustion Plant Directive

The EU revised LCPD defines emission limit values (ELVs) for sulphur dioxide (SO<sub>2</sub>) for combustion plant based on installation date, fuel and capacity. The LCPD control period commences on 1<sup>st</sup> January 2008 and most coal-fired power plant will continue to operate until at least then. From 2008 onwards, coal-fired plant must have FGD equipment, or accept limited hours derogation defined as 20,000 hours further operation until plant closure by end-2015.

The initial deadline for generators to choose whether or not to comply with the LCPD passed on 30<sup>th</sup> June 2004. Almost 13GW of coal-fired plant capacity opted into compliance and around 14GW opted out [3]. Nearly all of the UK's oil-fired stations were opted out. However, the decision as to whether the UK Government will directly apply the European Union's Emission Limit Values (ELVs) or impose its own National Emission Reduction Plan (NERP) remains open and the UK Government have stated that they will allow opted out plant to opt back in at anytime up until the 1<sup>st</sup> January 2008 compliance date. Given this concession, generators are delaying decisions over whether to commit to significant investment in upgrading old coal plant with FGD, without clarity over whether such a decision would prove economic, or build new CCGT plant.



### 15.2.3 Power Prices

Utility CCGT/CHP and conventional thermal plant are required to compete against each other under the New Energy Trading Arrangements (NETA), which became the British Electricity Trading and Transmission Arrangements (BETTA) on 1<sup>st</sup> April 2005. As a result of the opening of electricity markets and over capacity under NETA, wholesale electricity prices fell initially, at times matching, or even falling below, marginal costs. Most industrial CHP plants have also struggled under NETA trading conditions. Consequently, there has been a degree of turmoil within the market over recent years. This has resulted in significant consolidation, with five or six major power producers operating at present.

Fuel prices are one of the key determinates of generation costs, as a generators' profit margin is the difference between the fuel purchase price and the price of power sold. The gas power differential is known as the spark spread, whilst the coal power differential is known as the dark-spread.

Over the past year, there has been reasonable recovery in the market for coal-fired generation, with the dark spread increasing from around £10/MWh to £20/MWh. However, there has been little recovery in the spark spread for gas plant, which has remained relatively constant at around £8-9/MWh. Consequently, the profitability for gas fired generation has remained marginal. Over the next few years, an increase in spark spread is required to promote suitable market conditions for new gas plant entrants.

### 15.2.4 Future Construction

National Grid Transco (NGT) require a plant margin of around 20% between demand and generation in accordance with governmental responsibilities for ensuring sufficient and reliable power generation. NGT published its 'Severn Year Statement' in 2004, with plant margins for the UK transmission system for the years 2004/05 to 2010/11 reproduced below (Table 15.1) [4].

	2004/5	2005/6	2006/7	2007/8	2008/9	2009/10	2010/11
Demand, MW	62,042	63,124	64,282	65,086	66,117	67,053	67,963
Generation, MW	75,476	77,690	79,364	85,039	85,610	86,960	87,180
Plant Margin %	21.7	23.1	23.5	30.7	29.5	29.7	28.3

**Table 15.1: UK Plant Margin (%) [4]**

Up to 2010, new capacity requirements are likely to be provided by new build gas-fired CCGT plant, which requires the lowest capital investment and shortest lead time in comparison to potential coal and nuclear build (Table 15.2) [4]. Five major CCGT plant projects are planned currently, with a controlling interest held by one of the major energy retailers (Table 15.3) [5]. However, there is no guarantee that all of these schemes will all go ahead unless UK and EU energy policy and market conditions are supportive of investment.

<b>Type</b>	<b>2004/5</b>	<b>2005/6</b>	<b>2006/7</b>	<b>2007/8</b>	<b>2008/9</b>	<b>2009/10</b>	<b>2010/11</b>
Nuclear	12,134	11,984	11,086	11,086	10,616	10,616	9610
Coal	24,628	24,628	24,628	24,628	24,628	24,628	24,628
Gas	25,179	26,009	26,839	30,737	30,737	31,047	31,047
Dual fuel	4050	4050	4050	4050	4050	4050	4050
Oil	3552	3922	3922	3922	3922	3922	3922
Interconnectors	1988	1988	1988	2588	2588	2788	3308
Hydro + Pumped Storage	3221	3221	3788	3892	3892	3892	3892
Onshore + Offshore Wind	648	1811	2987	4060	5101	5941	6647
Oth. Renewables + CHP	77	77	77	77	77	77	77
<b>Total</b>	<b>75,476</b>	<b>77,690</b>	<b>79,364</b>	<b>85,039</b>	<b>85,610</b>	<b>86,960</b>	<b>87,180</b>

**Table 15.2: UK Generation by Plant Type (MW) [4]**

Plant Name	Parent	GW	When
Langage	Centrica	1.0/1.3	2008-10
Marchwood	ESBI	0.9	2007
Staythorpe C	RWE	0.8	2006
Grain	E.ON	2.4	2010
Pembroke	RWE	2.0	2010

**Table 15.3: Major Proposed Generating Projects [5]**

Longer term (2010 to 2020), there is greater uncertainty regarding the exact portfolio of energy sources in the UK, although significant gas generation is likely. A number of industrialists have championed the need for a balanced portfolio of energy sources, including gas, clean coal, renewables and possibly nuclear as part of a long-term policy framework to encourage investment.

#### 15.2.5 UK Industrial Market

There are two types of power plant within the UK industrial market:

- package boilers, which generate either electricity or heat independently of each other;
- Combined Heat and Power plant (CHP), where electricity and useful heat are both generated simultaneously.

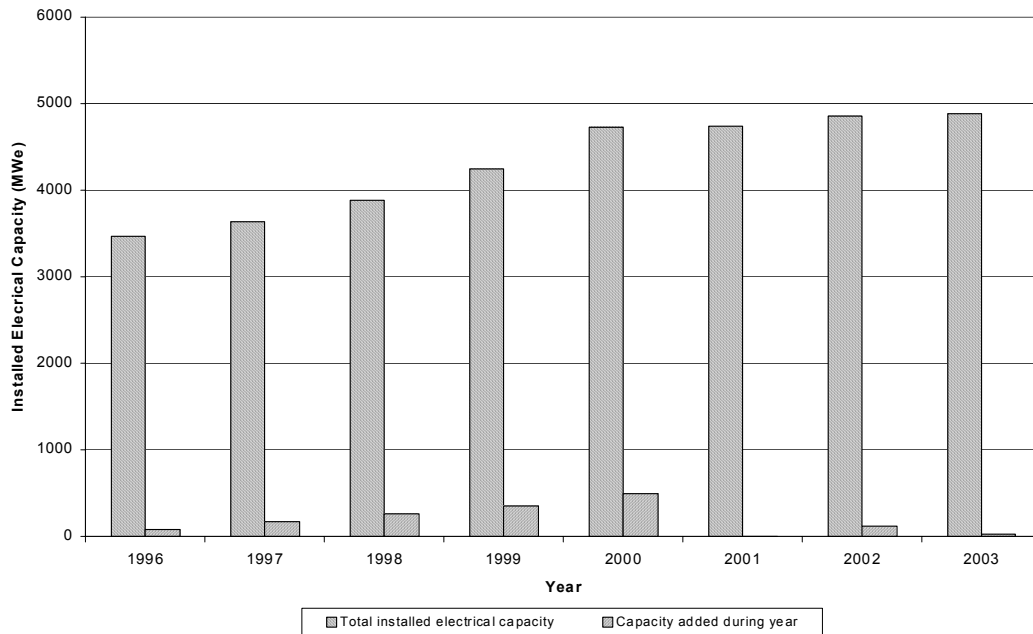
The annual Directory of UK Energy Statistics (DUKES) for 2004 gives various data for CHP schemes in the UK [6]. The data is gathered through the Government's CHP Quality Assurance scheme. The majority of schemes are fuelled with natural gas or by-product fuels. Most CHP schemes are small scale, but with generating capacity dominated by the minority larger schemes (Table 15.4).

Electrical capacity size range	Number of schemes	Total capacity MWe
< 100 kWe	628	38
100 kWe to 999 kWe	624	149
1 MWe to 9.9 MWe	182	733
10.0 MWe and above	72	3958
Total	1506	4879

**Table 15.4: CHP Installations by Capacity and Size Range, 2003 [6]**

The UK Government has set a target of 10GWe of CHP capacity to be installed by 2010, which it has now acknowledged will not be achieved. The latest projections for CHP capacity, undertaken by Cambridge Econometrics and published in November 2003, were for 6.4GWe in 2005 and 8.1GWe in 2010 [7].

The installed CHP capacity in the UK since 1996 is shown in Figure 15.2 [6].



**Figure 15.2: Installed CHP capacity in the UK 1996 – 2003 [6]**

The chart shows that in the 1990s, growth in CHP capacity was accelerating, with the rate peaking in 2000 with 844MW of plant being commissioned. However, from 2001 onwards, the market has slowed down considerably. Whilst the 734MWe Conoco Philips Immingham CHP plant began commercial operation in Autumn 2004, the legislative and economic environment for CHP has changed markedly over the last few years. The only CHP projects that are likely to go ahead currently are those where all power is consumed on site. This has seen greater recent construction of package boilers for electricity or steam production at industrial sites, rather than CHP plant.

Whilst power prices have recovered from initial falls following the introduction of NETA, the CHP market remains unattractive for developers. This is mainly due to continuing high gas prices and reductions in steam demand from industrial hosts, making the economics of CHP plant operation unfavourable. Additionally, developers require long term commitment and partnership with the host customer, which is becoming increasingly difficult to sustain with the state of the UK industry. Many developers have now lost money on CHP schemes and are unwilling to invest further until there are clear incentives to do so.

The Government's Strategy for CHP to 2010 was published in April 2004 [8]. This document sets out the range of measures introduced to support the growth of CHP capacity. However, this has not been sufficient to stimulate a recovery in the CHP market and stronger incentives are required. The Combined Heat and Power Association (CHPA) has identified key Government opportunities for support as exemption of CHP from the cost burden of the Renewables Obligation, and are lobbying to ensure that the EU Emissions Trading Scheme actively promotes CHP. A proposal has been put to Government (the Whitehead Proposal) that would guarantee a spark spread for CHP operators and is strongly supported by the CHPA. This would promote

not only the current operations of CHP plant already running, but also provide an incentive for new build

### **15.3 Western Europe**

The power market situation in Western Europe is similar to that of the UK in many ways. In Western Europe, relatively slow growth in electricity demand is expected over the next twenty years, with an average projected increase of 1.3% per year. In general, there is limited need for new capacity in the near future, except in countries where nuclear power is being phased out. However, the European Commission and other major institutions have forecast a shortfall in power plant capacity across Europe of around 200GW by 2020 due to the need to replace existing nuclear and conventional thermal plant facilities from the end of this decade onwards [9]. Germany has particular problems, with an additional 40GW of power capacity needed by 2020 due to the decision to phase out all nuclear plant.

At present, uncertainty regarding both the regulatory environment and the electricity price has delayed long term investments being made in new generating plant. The European market for electricity has become increasingly deregulated and competitive, and environmental regulations increasingly stringent. Natural gas is projected to gain share throughout the region due to efficiency and environmental advantages over other fossil fuels, but the availability of gas will be dictated by expansion of the European supply network. The European carbon trading scheme is likely to be a decisive factor in coal's future role, determining how profitable coal plant will be in comparison to gas-fired stations.

In the industrial CHP market, the EU target is to double capacity as a fraction of total generation capacity from 9% (1994) to 18% in 2010 [10]. However, the CHP market in the EU has remained largely inactive in recent years due to the initial decline in power prices following the liberalisation of the electricity market. The outlook for CHP plant has started to improve, with rising power prices, the introduction of the EU Cogeneration Directive in 2004 and emissions trading beginning to change market conditions.

### **15.4 Eastern Europe and the Former Soviet Union**

Much of the equipment installed in Eastern European countries and in the Former Soviet Union (FSU) is of relatively old, low-efficiency Soviet-era design [11]. There is a good market for power plant equipment in these countries at present due to the need to replace ageing and inefficient plant and to improve environmental performance. Fossil fuels play a major part of the power portfolio and will continue to do so for the foreseeable future.

In Eastern Europe, the market drivers in the power generation field vary depending upon whether the country in question has recently joined the EU or whether EU membership is anticipated at a later date. For those countries which have recently joined the EU (Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, the Slovak Republic and Slovenia), the majority of the plant rehabilitation necessary to meet acceptable levels of efficiency and availability has been undertaken and one of the main drivers for these countries is the provision of modest amounts of additional capacity to meet demand growth. For the accession states (including

Romania and Bulgaria), the main drivers are the rehabilitation of existing power plant in order to meet increasing electricity demand and the installation / planned installation of emissions abatement technology.

Countries in the FSU have seen several years of positive economic growth, increasing the demand for secure supplies of electric power. Generation from fossil fuels, mostly natural gas and coal, is prevalent in most of the countries where resources are significant, and is expected to continue to be so. Russia has large oil and gas reserves and the Russian fuel mix is heavily dependent on natural gas. There has been concern recently regarding the country's over-reliance on gas and increased investment in nuclear plant has been proposed. Russia is currently the world's largest gas exporter, which may also impact upon indigenous fuel use for power plant.

### **15.5 North America**

The power generation market in North America is dominated by the USA. Electricity demand in the USA is projected to increase relatively slowly over the next twenty years, with an average annual growth rate expected of 1.8%. A growth rate of only 1.4% is projected for the North American region as a whole.

In the USA, generation over capacity in places is likely to result in relatively little new build activity in the short term in comparison to the size of the network. Most new capacity additions will be coal-fired projects. Rising gas prices have improved the cost competitiveness of coal-fired technologies and natural gas is not expected to play an important role as a fuel for base load power generation. The USA has the largest share of the world's recoverable coal reserves and some 112GW of new coal-fired generating capacity is expected to be built by 2025.

### **15.6 China**

China represents the largest single market in the world for new power plant equipment. With high rates of Gross Domestic Product (GDP), electricity demand has grown significantly for a number of years. Over the past five years, electricity consumption has risen by an average of 7.2% annually, and is projected to rise by an average of 4.2% per year up to 2030.

Coal is the main source of fuel for power generation in China, utilising extensive natural reserves. This situation is not expected to change in the foreseeable future. Significant growth in gas plant is expected, mainly at coastal locations via the supply of Liquefied Natural Gas (LNG), but the overall contribution of gas to the generation mix will remain small in comparison to coal.

The use of coal is expected to grow substantially up to 2030, with the installation of new large scale boiler plant. The Chinese Government has begun to promote the construction of new coal-fired power plant in response to growing electric power shortages. Annual electricity generation from coal was 1081TWh in 2000, which is projected to rise to 1723TWh in 2010 and 3503TWh in 2030. China is actively pursuing Clean Coal Technologies (CCTs) as a means of meeting future energy requirements, with supercritical boilers and Integrated Gasification Technology (IGCC) attractive options.

## **15.7 India**

In developing Asia, India has the second largest installed capacity (100GW), behind China. Electricity demand is projected to increase by 3.3% per year up to 2025 due to strong economic growth. The power sector is dominated by coal and use is projected to increase threefold from 2000 to 2030. Liquefied Natural Gas (LNG) may be used at some new power plant at coastal locations.

India has an overall power shortage of around 8 to 10% and substantial additional capacity is required. Whilst the current target for building new capacity is a further 100GW by 2012, there have been a number of problems financing new investment. Even though private investment in the electric power sector is allowed, increasing capacity through foreign investment is viewed as difficult as many companies find the country's bureaucracy onerous. Some 25GWe of existing capacity is captive power, which has been built by businesses requiring security of supply and is not available to the national grid.

## **15.8 Other Asian Countries**

In other countries of developing Asia, demand for electricity is expected to grow by around 2.8% per year up to 2025. Although a significant proportion of the region's electricity is generated by coal-fired power plant, the share of gas-fired generation is projected to increase. Reducing environmental emissions from coal-fired plant is an important issue for the region.

Japan has a mature electric power industry and only modest growth in demand is expected in the mid-term. Japan's electricity is produced mainly from fossil fuels and nuclear power. Whilst there have been recent problems in Japan's nuclear power industry, resulting in increased generation from fossil fuels to compensate, more nuclear capacity is planned for the future.

## **15.9 Middle East**

The Middle East has a large power industry, with over 100GW of installed capacity [12]. Electricity demand is projected to increase by 2.8% per year on average over the next two decades.

A number of countries in the region have large reserves of petroleum and natural gas, which are expected to dominate electricity generation. In many cases, flare gas from oil refineries is used to produce power in open-cycle gas turbines, where reliability of power supply is more important than plant efficiency.

Whilst the electric power sector is state owned in many countries, some countries, such as Saudi Arabia and Qatar, have opened up their electricity markets in an effort to attract foreign investment. Private investment in power projects has been used for a series of water and power projects, with water availability of increasing importance in the region. In these projects, large power facilities have been built as cogeneration plant with steam export to associated thermal desalination works.

## 15.10 Australia

Electricity demand in Australia is expected to increase by 2.5% per year up to 2010. Whilst Australia depends heavily on coal for power generation at present and has large domestic reserves, gas is likely to be used increasingly for additional capacity in the future, largely displacing oil and, to a lesser extent, coal.

## 15.11 Africa

South Africa has Africa's largest electric power sector by some margin and has also become a major regional supplier of electricity. Eskom, the state-owned electric power company, generates nearly all of South Africa's electric power, mainly through coal-fired power plant. Eskom has recently launched a programme for the expansion of its generating capacity, including the refurbishment and upgrading of existing pulverised coal generating units, as well as building new fossil fuel based power plant (gas turbine and possibly super critical pulverised coal units).

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## 16 UK ACTIVITIES

This chapter reviews the prospects and capabilities of UK suppliers and manufacturers in the global water treatment plant market associated with fossil fuel based power plant. Research, development and demonstration (RD&D) in the UK is also discussed.

### 16.1 UK Power Plant Developments

#### 16.1.1 Demineralisation Plant

The UK power industry has seen significant developments in demineralisation plant technology from systems installed in conventional coal-fired power stations in the late 1960's to early 1980's in comparison to treatment plant in modern CCGTs built from the 1990's onwards.

The original water treatment plant installed at conventional coal-fired stations consisted generally of co-current regenerated plant treating towns main water. In modern CCGT plant, ion exchange remains the predominant technology installed in new plant, but with much improved designs by comparison. Packed beds and counter current regeneration have now become standard, with cation polishers often used in place of mixed bed units.

Despite advances in water treatment technology, particularly in membrane systems, the UK power industry has generally remained conservative in its adoption of new technology. In many instances, this has been due to the risk averse nature of the industry, where the primary driver is for safe and reliable generation of electricity. Many of the older coal-fired stations still use ion exchange to treat towns main water or borehole water at sites where raw water abstraction licences and wastewater discharge limits do not impact on choice of demineralisation plant technology. In recent years, there have been significant cost pressures within the power industry to reduce expenditure on capital plant, which has further limited investment in water treatment systems.

Although advanced membrane systems (microfiltration, reverse osmosis, electrodeionisation) are now used for water purification at a number of utility power plant sites, this has generally been as a result of significant economic or environment drivers for on-going power plant operation, rather than as a willingness to upgrade old plant. Where microfiltration and reverse osmosis systems have been installed, this has generally been in pre-treatment plant retrofits, where there have been particular site specific drivers for capital investment in new membrane plant.

#### 16.1.2 Water Treatment Outsourcing

Within the UK power industry, there has been an increasing trend of outsourcing water treatment. Outsourcing has proven to be an attractive alternative to capital investment in new water treatment plant on the basis of through-life costs, both for old stations with limited expected remaining operation and for new build stations. Outsourcing has also been an attractive option for plant operators through the obviating of risk associated with loss of demineralised water production.

There has also been a general trend of reducing manpower and technical expertise at power plant, which has further increased reliance on service providers for water treatment plant operation and maintenance and for technical advice. In modern gas-fired plant in particular staffing levels are often reduced to the minimum required for site operation.

Sites with outsourced demineralised water production have tended to see wider application of advanced technologies, such as membrane systems, in comparison to sites undertaking water treatment plant operation and maintenance in-house. In these cases, the selection of treatment technology has largely been the responsibility of the service provider, rather than the plant owner or operator.

### 16.1.3 Flue Gas Desulphurisation

The current UK FGD market is dominated by retrofit projects to bring the fleet of coal-fired power stations into line with the SO<sub>2</sub> emission reduction requirements of the revised Large Combustion Plant Directive (LCPD) set to come into force on 1<sup>st</sup> January 2008. As of the preliminary compliance decision date of 30<sup>th</sup> June 2004, 13.4GW of the UK's current 32.3GW capacity of coal and oil fired generation capacity had opted in to the LCPD. Of the coal-fired power stations opted in to the LCPD, 6GW (Drax and Ratcliffe) already have limestone gypsum FGD equipment in commercial operation and 0.4GW (Uskmouth) has a semi-dry process installed. Of the remaining 7GW of opted in plant, 5GW (Cottam, Eggborough and West Burton) currently have limestone gypsum FGD under construction, whilst the remaining 2GW (Aberthaw and Kilroot) are understood to have applied for Section 36 consent to install the seawater FGD process. With the ruling from the UK Government that any plant may opt back in before 1<sup>st</sup> Jan 2008 (as discussed in Section 13), this situation may change. However, the lead time associated with obtaining consent, placing the contract and constructing an FGD plant may soon reach a point at which it will not be possible to have the FGD system operational by the 1<sup>st</sup> Jan 2008. McIlvane (2005) suggest that the lead time for FGD construction alone is currently around two to four years.

## **16.2 Prospects of UK Suppliers and Manufacturers in the UK and Global Market**

### 16.2.1 Overview of UK Suppliers

The UK has retained few major original equipment manufacturers (OEMs) of water treatment plant equipment for the power industry. There are now two main UK-based companies, Christ Kennicott Water Systems Limited and Elga Process Water (Veolia Water Systems) that have traditionally serviced the power industry and that have retained most UK expertise in this field. The trend of increasing consolidation amongst the major water and wastewater treatment companies worldwide has also been evident in the UK and both of these businesses are now owned by overseas parent companies.

There are also a number of smaller UK OEMs that operate in the field of industrial water treatment, both domestically and overseas. These exist both as independent companies and as subsidiaries of larger organisations. Within the power industry, there has been some success amongst these companies for the provision of water treatment plant for small scale industrial plant and CHP schemes, rather than for utility plant. A

number of the smaller companies also provide outsourced water treatment plant service contracts to power plant sites.

### 16.2.2 EPC Contracts for Power Plant

New power plant projects, both within the UK and worldwide, are typically placed as an overall engineering, procurement and construction (EPC) contract by the company or organisation commissioning the project.

There are no major UK-owned power plant EPC contractors, although in principle a UK company with process design capabilities could take on an EPC contract and design the plant under license, sub-contracting work and equipment supply as necessary. For new utility power plant projects within the European market, the main players for EPC contracts are likely to be Siemens, Alstom Power, Bechtel and Samsung Heavy Industries.

In the industrial power plant market, the smaller scale of most plant means that projects may be managed by plant owners, by owners' engineers, or placed as EPC contracts. A greater number of companies are also able to offer suitable competencies for industrial EPC contracts in comparison to utility power plant build.

In EPC contracts, the water treatment plant build is generally subcontracted by the main plant contractor. Therefore, in order for a UK based water treatment plant equipment supplier to successfully provide components to a particular project, either within the UK or overseas, the supplier would have to win a contract with the EPC contractor, which is likely to be decided by a tendering process.

EPC Contractors tend to do business with preferred suppliers for balance of plant items, including water treatment plant. There can be an immediate disadvantage for UK firms if the company policy of an overseas EPC contractor is to employ vendors from its home country where possible. Additionally, major power plant contractors, such as Siemens and GE, are now also able to supply water treatment plant equipment as part of extensive in-house capabilities and power plant packages. Although this has not had a major effect on projects to date, discussions regarding future co-operation and inter-trading between power plant engineering and water treatment divisions are generally at an early stage. Some UK companies are already compensating for this by accommodating equipment from the EPC contractor's water treatment division in project tenders. However, the purchase of new water treatment plant by EPC contractors is currently driven by the primary objective of reducing capital costs to a minimum. EPC Contractors now tend to procure both locally and globally in order to achieve this. In general, water treatment plant civil works and bulk commodities (cabling and piping) are sourced locally, with equipment sourced globally as a package. Therefore, there is expected to be increasing competition between domestic and international companies for new power plant water treatment contracts worldwide, particularly for utility scale plant build.

### 16.2.3 Current Perception of UK Companies amongst EPC Contractors

EPC Contractors have identified the following main current limitations for UK companies in the global market:

- loss of in-house capabilities relating to manufacture and installation, particularly amongst the larger OEMs;
- pressures to reduce capital costs resulting in low quality water treatment plant build.

UK companies are no longer seen as being able to offer the full range of in-house design, manufacturing and installation capabilities in comparison to historical competencies. This is largely as a result of firms diversifying into alternative active market sectors in order to sustain business due to lack of work from the power industry, primarily from the UK but also from overseas. In new build projects that have gone ahead, there have been significant pressures on clients to reduce expenditure on capital plant, which has been passed downwards to main contractors and, in turn, to water treatment plant suppliers. This has often resulted in contracts being awarded to cheaper overseas suppliers benefiting from a low cost manufacturing base, creating some indifference amongst UK companies in bidding for more projects. For most UK suppliers, the power industry is now responsible for only a small percentage of income, with municipal water and wastewater, pharmaceutical and semiconductor industries providing a large proportion of current business. Consequently, some loss of skills and experience within UK companies for power plant projects has to be expected.

The aim of minimising capital expenditure dominates new power projects and a number of UK water treatment companies now import standard plant components from China, India and Eastern Europe in order to reduce manufacturing costs. However, the quality of components manufactured cheaply overseas has typically been poor. For UK firms importing such components, this has often resulted in a decline in the overall quality of plant supplied in comparison to the standards achieved historically when undertaking manufacturing in-house or in the UK. This has resulted in additional costs and much greater engineering effort on behalf of main power plant contractors to fully commission water treatment plant, either requiring increased project management to ensure that quality standards are adhered to during build, or additional costs and financial penalties for project delays whilst undertaking water treatment plant repairs. Whilst capital cost still remains the key driver in new water treatment plant contracts for EPC contractors, the engineering risk associated with cheaper plant can result in greater cognisance for improved build quality in tender assessments.

#### 16.2.4 General Prospects for UK Companies

The generic factors that affect the prospects of UK companies in winning work for new power plant projects include:

- Cost effectiveness, i.e. low capital cost;
- Technical competency;
- Proven expertise in power plant projects;
- Satisfactory staff resource;
- Adherence to quality standards for design and manufacture;
- Low commercial risk.

In these respects, the larger UK OEMs, specifically Christ Kennicott and Elga Process Water, remain best placed amongst UK firms for new utility and industrial power plant contracts, with well established contacts with main contractors, proven expertise and

partnerships and licensing agreements. Synergies with other businesses and subsidiaries within the company group can also provide benefits with respect to technology transfer and project opportunities.

Amongst the smaller UK companies consulted, there had been some success in winning new build contracts for small scale UK industrial power plant projects, which is expected to continue. In these projects, companies had remained cost competitive in comparison to both larger firms and overseas suppliers due to lower overheads and flexibility of cost margins. Whilst there was a general perception amongst consultees from smaller businesses that projects of any size within the power industry would be welcomed and could be catered for, there would be reluctance on the part of EPC contractors to place utility contracts with such suppliers due to lack of technical experience with large power plant construction projects and commercial risks associated with the size of company.

For the smaller UK suppliers, lack of awareness of company presence and capabilities and lack of proven power plant expertise were all cited by main plant contractors as limiting business opportunities in the power industry. The smaller suppliers themselves expressed difficulties identifying active projects to pursue. For the smaller UK companies to be utilised significantly in new power plant projects, it is essential for interested suppliers to establish and maintain contact with EPC contractors. This would also provide a direct way of gaining insight into projects for which tenders were being sought. However, this would be dependent on sufficient resource being available within the company to undertake such activities and is unlikely to be a priority for a market where there are few project opportunities at present.

#### 16.2.5 FGD Waste Water Treatment Plant Projects

FGD projects are also placed typically as an EPC contract between the utility company commissioning the work and an EPC contractor, who may be the original FGD process licensor, or a single contractor or consortium acting as a licence holder. In a new build power plant, the FGD supplier may be subcontracted by the overall power plant EPC contractor. In some recent projects, particularly in the USA, FGD retrofit projects have been undertaken under an alliance contract, in which a collaborative approach is undertaken with benefits reported to include shared risks, mutually aligned incentives and elimination of unnecessary contingencies.

In order for a UK based supplier of waste water treatment plant to successfully provide components to a particular FGD contract, the supplier would again have to successfully win a contract with the EPC FGD supplier. The FGD suppliers and licence holders known to be active in the worldwide FGD market at present are Alstom, Austrian Energy and Environment, Babcock & Wilcox, Chiyoda, FLS, Fortum, Fujikasui, Idreco, IHI, Lurgi Lentjes Bischoff, Marsulex, Mitsubishi Heavy Industries (Advatech), RWE Solutions, Stone & Webster US, Wheelabrator and Wulff. There are no major FGD process licence holders based in the UK.

#### 16.2.6 Service Contracts for UK Power Plant

Growth in the UK power market for outsourced water treatment service and maintenance contracts is expected to continue. A number of power stations still carry

out work in-house, but there is a general trend of reduced manpower and technical expertise within the industry, particularly at gas-fired plant. This has facilitated greater use of service contracts for water treatment plant maintenance. In the short term, most new build power plant is expected to be gas-fired and so this trend is expected to continue.

For new build power plant in the UK, increased competition for capital water treatment plant is expected to come from overseas companies. Most overseas OEMs do not have extensive UK capabilities for service provision during plant operation, which could present further opportunities for service contracts amongst UK suppliers.

#### 16.2.7 World Bank Projects

The sponsorship of World Bank power plant projects by UK banks is seen as an opportunity for generating return business for UK companies that is not being fully exploited at present. In these projects, some plant equipment should be sourced from the home countries of sponsors (within EC rules), which acts as a form of recovering capital investment for the country. However, the UK is perceived as not been very adept at this type of business in comparison to other countries. World Bank projects require the world's best environmental standards for plant, rather than those required by indigenous governments, which would need to be met by any participating UK supplier.

#### 16.2.8 Long-Term Maintenance of Expertise

A number of consultees expressed concern regarding the ability of UK companies to sustain expertise in the long term due to difficulties attracting skilled personnel into the industry for staff succession. Few training opportunities or apprenticeships were considered to be available for the development of inexperienced staff.

### **16.3 UK Manufacturers and Suppliers**

The following water treatment companies are UK owned, or represent a major manufacturing or engineering design facility in the UK. Company contact details are provided in Appendix D.

#### Christ Kennicott Water Technology Limited

Christ Kennicott is generally viewed as one of the largest water treatment plant OEMs for the power industry now operating from the UK, along with Elga Process Water. Christ Kennicott in the UK employs 50 full time staff and 10 contract engineers.

Thompson Kennicott was bought by the Best Water Treatment group in 1998 as part of the group's acquisition of synergistic water treatment companies across Europe. Kennicott is now part of the Power Generation business unit under the Christ brand name. Access to water treatment technologies and products held within the Christ group, particularly membrane plant, has allowed Christ Kennicott to enhance its range of engineering and project options.

Christ Kennicott has a wide base of installations throughout the world and has provided plant for boiler feed water and process water treatment from small 60 MW gas turbine

stations to 2000 MW nuclear power plants. Both pre-treatment and wastewater systems can be provided as turnkey packages. Condensate polishing is a particular area of expertise via Kennicott's CONESEP® system. The CONESEP® design has been installed recently in a large number of condensate polishing applications in power plant in China and India via local licensees.

#### Elga Process Water (Veolia Water Systems Limited)

Veolia Water Systems specialises in the provision of services and equipment for industrial and municipal water and wastewater treatment schemes, including major, custom engineered and design, new plant build. Leading brands within Veolia Water Systems include Elga Process Water, Elga LabWater, MTI, Edwards and Jones, OTVB and Permutit. Veolia Water Systems has a number of reference water treatment plant installations at UK power stations, including the Cottam reverse osmosis retrofit plant installed in 2001.

In September 2003, Veolia Water Systems relaunched its purified water treatment activities under the brand of Elga Process Water. Elga Process Water offers the full range of water treatment technologies for boiler feedwater production, including filtration, demineralisation and reverse osmosis. Mobile water treatment units can also be offered through Elga's Aquamove business. In the UK and Ireland, Elga has over 350 staff operating across three sites.

Elga is active within the UK power industry through the provision of maintenance contracts and in new water treatment plant projects. Elga is currently installing a new reverse osmosis demineralisation plant at the Fiddler's Ferry 2000 MW coal-fired power station and is also providing water treatment plant for the IneosChlor and Pfizer new build industrial power plant schemes.

#### ACWa Services Limited

ACWa Services Limited is an environmental company specialising in the design and construction of water, effluent and air purification systems. ACWa was established in 1986, and has been part of the Consolidated Contractors Company (CCC) Group of Companies since 1991. ACWa has provided engineered solutions worldwide, with capabilities including process design and complete turnkey installation, through to operation and maintenance. Technologies offered include microfiltration, ultrafiltration, reverse osmosis and mixed bed ion exchange for the production of high purity water for process applications. Reference installations at UK power plant include a 2 x 720m<sup>3</sup>/d microfiltration plant followed by reverse osmosis treating sewage effluent for boiler feed at Centrica's Peterborough CCGT power station, which was commissioned in October 2000. A 300m<sup>3</sup>/d reverse osmosis plant followed by mixed bed deionisation has also been installed at British Sugar's Bury St. Edmonds site, treating borehole water for high purity boiler feed.

#### Alpheus Environmental Limited

Alpheus Environmental is a service company offering outsourced operation and maintenance of water and wastewater facilities to customers within the UK. Alpheus is a wholly owned subsidiary of Anglian Water.



In the power industry, Alpheus has a ten year Build Own Operate contract for the membrane plant treating sewage works final effluent for boiler make-up at Peterborough CCGT power station. Alpheus has also secured a contract to maintain E.ON UK's reverse osmosis water treatment plant at Ratcliffe Power Station.

#### Anderson Water Equipment

Anderson Water Equipment (AWE) of Cardiff designs and manufactures bespoke water purification systems. Manufacturing is sub-contracted to companies within the UK. Technologies offered range from basic filtration through to demineralisation and reverse osmosis. AWE works across a number of industries, including power plant applications. AWE provided the water treatment plant for E.ON UK's Port of Liverpool CHP site (2 x 105m<sup>3</sup>/hr) and has also won service contracts for water treatment plant at utility power stations.

#### Derwent Water Systems

Derwent Water Systems of Matlock manufactures and supplies water treatment plant, ranging from basic water softeners and reverse osmosis equipment to customer specified water treatment solutions. Equipment is sourced locally and control and instrumentation parts manufactured in-house.

Derwent has been involved in a number of power plant projects in the UK, including the supply of demineralisation systems of around 20 to 50m<sup>3</sup>/hr throughput for boiler feedwater. Most power industry business has been servicing contracts, ion exchange resin bed replacement and general refurbishment work.

#### Ecolochem International Limited

Ecolochem International Inc of Peterborough is a global leader in the provision of mobile emergency and short-term water treatment equipment and in the provision of long-term outsourced industrial and power plant water treatment service agreements. Strategic equipment depots are located throughout Europe and Asia. Both stand alone technologies and complete turn-key purification systems can be supplied.

In recent years, there has been significant business for Ecolochem from the UK power industry. This has included the provision of emergency water treatment plant services and complete outsourced demineralised water production for power plant both with limited remaining operation life and for new build stations. Ecolochem has recently provided a complete outsourced water treatment facility for the new build 860MW Interger CCGT plant in Spalding.

Ecolochem is now part of the GE Infrastructure Water and Process Technologies group, having previously been acquired by Ionics Inc. in 2004.

#### Environmental Water Systems Limited

Environmental Water Systems Ltd (EWS) specialise in water purification and wastewater treatment, including the design, manufacture and supply of reverse

osmosis, filtration, demineralisation and base exchange softeners capable of treating flows of up to 60 – 70m<sup>3</sup>/hr. Whilst EWS mainly provide maintenance services at present, growth is planned in industrial sales through the provision of capital plant and replacement equipment. EWS has recently moved to larger premises in order to accommodate a manufacturing facility. In the power industry, EWS has a number of service contracts.

#### Esmil Process Systems Limited

Esmil Process Systems Ltd of High Wycombe provides water treatment solutions. This typically involves membrane technology for 'zero discharge' industrial wastewater treatment and recovery schemes and process systems for the treatment of produced water and other similar applications. Esmil provides design, project management and commissioning capabilities for projects typically between 5 to 100m<sup>3</sup>/hr in size. Component build is sub-contracted out, generally within the UK. Whilst Esmil remain interested in power plant projects, they now mainly target high value industrial projects due to heavy competition for standard equipment in power plant applications.

#### Memcor Limited

Memcor Ltd specialises in the manufacture of microfiltration membranes for water treatment plant. Reverse osmosis plant can also be provided, but only account for a small percentage of business sales. Memcor was originally part of an Australian owned group of companies acquired by USFilter in 1997. USFilter was then bought by Siemens in 2004. Memcor now operates as a stand alone business unit within the Siemens Water Technologies division. Memcor manufactures its own fibres and membranes in its plant in Australia. Additional equipment can be sourced from the USFilter parent company.

In the UK, Memcor employs thirty-five people at an office base in Derby, which provides product construction, research and development, engineering and management and long-term maintenance capabilities for the company within Europe and the Middle East. In the UK, Memcor has had considerable success with microfiltration unit installations for municipal water treatment. In 2001, microfiltration membranes were also installed at the 2000MW coal-fired Cottam power station to provide pre-treatment of cooling water for a retro-fit reverse osmosis demineralisation plant.

#### PURAC Limited

PURAC is a process engineering and contracting group specialising in municipal and industrial water and wastewater treatment. PURAC became part of Anglian Water in 1993, but has been in business of more than 40 years. PURAC has completed projects in over 50 different countries and is one of the largest process engineering entities in Europe.

PURAC has designed a number of reverse osmosis plants in recent years and also hold a license to market ZENON membranes in the UK and Republic of Ireland. In the UK power industry, reverse osmosis water treatment plant have been installed at High Marnham (3.6MLD), West Burton (4.8MLD) and Ratcliffe (90m<sup>3</sup>/hr) Power Stations. In each case, pre-treatment was provided by ZENON submerged ultrafiltration units.

## Satec Limited

Satec specialises in water, waste water, sewage and effluent treatment, as well as supplying on-going service and spare parts, both in the UK and overseas. Capabilities include supply and commissioning of new systems and turnkey contracting. Satec has expertise in all aspects of core water treatment, including ion exchange, reverse osmosis, media filtration, clarification and thermal deaeration. Satec offer modular designed standard packaged plant, which can range in size from 1 to 600m<sup>3</sup>/hr. Systems are designed in-house, with the build sub-contracted out.

## Sterling Hydrotech Limited

Sterling Hydrotech is a water treatment plant manufacturing and service company based in Derbyshire. Capabilities include design, installation, commissioning and complete turnkey contracts, as well as routine maintenance and serving contracts. Expertise includes dealkalisation, demineralisation and reverse osmosis treatment for industrial boiler feedwater.

## ZENON Environmental (UK) Limited

ZENON Environmental is a market leader in immersed membrane systems and has been designing and manufacturing low pressure hollow fibre polymeric membranes for 25 years. There are now in excess of 450 ZeeWeed<sup>®</sup> ultrafiltration installations throughout 40 countries in the World. Corporate headquarters are located in Canada.

In the UK, ZENON Environmental (UK) Limited is based in South Yorkshire. From these offices, projects are designed and managed for the industrial, water and waste-water markets throughout the UK and Ireland. ZENON ultrafiltration membranes are currently installed at Ratcliffe-on-Soar, West Burton and Kingsnorth power stations (note that Kingsnorth uses membranes relocated from the recently closed High Marnham station) where Purac Limited, a ZENON licensee, was the lead process contractor.

### **16.4 UK Research, Development and Demonstration Activities**

In the UK, there are no significant research and development activities within the field of industrial water treatment at present.

Most of the major UK-based equipment and product vendors for power plant water treatment applications are now owned by overseas parent companies. In general, research and development is carried out by the parent company in home countries, either in-house or through partnerships with domestic universities. Whilst some product development is undertaken amongst the smaller independent companies, this tends to be limited in scope due to the size of the business. In general, most companies are reliant on technology transfer from the major overseas equipment suppliers for advances.

Amongst UK universities, Cranfield, Newcastle, Glasgow and Newcastle have significant research interests in water treatment, use and management. Areas of expertise include membrane processes, absorptive media and filtration and flotation.

University water treatment research projects are initiated by funding from business or by government offices. However, there has been little interest from industrial companies, including the power industry. Current research areas are focussed primarily on applications for companies active in municipal water treatment and, to a lesser extent, potable water treatment, in order to support long-term strategic plans.

Previous approaches to universities have been made by the power industry for pure water applications, but the funding costs have generally proven prohibitive. Future power industry research projects for universities would need to come from a generic issue for companies, where syndicated projects could provide the leverage across businesses for research. Potential areas could include power plant water reuse schemes if there are moves from regulatory authorities in the future to reduce abstractions. Cranfield has expertise in this area, having been involved in the Peterborough power station project, where sewage works final effluent is used as raw water for boiler feed water production. However, there is no further interest in such schemes within the UK at present.

## 17 OVERALL CONCLUSIONS

### Current Status of Technologies

- The use of polymeric organic ion exchange resins for the deionisation of water is now a fully mature and developed technology. Modern ion exchange resins are stable high quality products which have made ion exchange a highly reliable process capable of producing high purity deionised water, even with poor pre-treatment or when subjected to substandard operating practices.
- Ion exchange currently remains the preferred and economic choice of treating water containing low total dissolved salts for the purpose of producing deionised makeup water. However, the continuing development of low pressure high flux membranes continues to lower the total dissolved salts barrier at which reverse osmosis systems can be competitive with conventional ion exchange.
- Ion exchange technology is currently the only effective option for condensate polishing applications in power plants. There are no available alternative membrane options
- Membrane microfiltration is replacing conventional clarification and filtration processes. However, waters with high levels of suspended solids still require to be treated by conventional clarification techniques
- Whilst in the last decade, worldwide, there has been a substantial growth in the application of membrane technology within the power industry. In contrast, within the UK, the assimilation of this new technology to produce process water for fossil fuel plants has been slow and conventional established treatment processes such as ion exchange remain the preferred option. This apparent reticence to adopt membrane technology is partly due to the conservative nature of the power industry to new technology and in part to the reluctance to invest in new plant and technology unless there is an overwhelming economic driver to justify such investment.
- The decision to install a straight ion exchange system (IX), reverse osmosis/mixed bed ion exchange (RO/IX) or reverse osmosis/continuous electrodeionisation system (RO/CEDI) will be based principally on economic drivers in terms of capital and operating costs, as well as regional requirements for chemical and waste water disposal. In many cases, familiarity with one or other technology is also a factor in the decision process.
- The capital and operating costs of any water treatment technology can only be determined by site specific evaluation due to the wide variability in the characteristics of the water to be treated and the water quality and quantity required by the various power plant processes.

### World Wide Activities

- The power generation industry is predicted to remain a very significant industrial market for water treatment equipment and associated supplies. Growth for water

treatment products in the power industry is expected to be typical of overall average growth in industrial water treatment markets.

- China represents a huge market for water treatment products and services, but is viewed as a difficult place to do business. Lack of intellectual property protection is a particular problem. Most overseas companies operating successfully within China have done so through maintaining an active local presence. Strong local players are emerging in the market and are expected to provide increasing competition for power plant water treatment contracts worldwide in the long-term.
- There has been significant rearrangement of ownership and increasing consolidation amongst water and waste treatment companies as major industrial corporations have moved to re-position themselves strategically to take advantage of developing opportunities in the water industry. General Electric and Siemens have emerged as major players in the water treatment equipment industry.
- Most major equipment and product companies now undertake manufacturing in China, India, other Southeast Asian countries and Eastern Europe in order to take advantage of low cost manufacturing facilities, but at some loss of quality in individual plant items.
- Membrane systems are likely to see greater future application as pressures on clean water availability increase the need to treat alternative low quality water supplies.

#### Market Potential

- Increases in future global electricity demand is expected to be met primarily through large scale fossil fuel based power plant. Whilst coal is projected to continue to retain the largest market share of electricity generation, natural gas fired generation is expected to become increasingly important. The main future markets for new fossil power plant are seen as China and India.
- In Western Europe, there is limited need for new capacity in the short term, except in countries where nuclear power is being phased out. However, significant new capacity will be required in a number of countries within the next 10 to 20 years, but uncertainty regarding both the regulatory environment and electricity prices is delaying long term investment in new generating plant.
- For countries in Eastern Europe and in the former Soviet Union, there is increasing need for the modernisation of existing plant and retrofits will be more important in the short-term.

#### UK Activities

- In the UK, the introduction of carbon emissions trading this year and the Large Combustion Plant Directive from 2008, combined with the retirement of most nuclear stations, could result in the need to replace almost half of the UK's power stations before 2016. In the short term, additional capacity is likely to be provided by the construction of new gas-fired plant. However, regulatory uncertainty and unfavourable market conditions are holding back investment in new plant by power generators.

- The UK CHP market remains unattractive for developers and stronger incentives are required to stimulate a recovery in the market. The only CHP projects that are likely to go ahead currently are those where all power is consumed on site. This has seen greater recent construction of package boilers for electricity or steam production at industrial sites.
- The UK has retained few major suppliers of water treatment plant equipment for the power industry. There are now two main UK-based companies, Christ Kennicott Water Systems Limited and Elga Process Water (Veolia Water Systems), which have traditionally serviced the power industry and that have retained most UK expertise in this field. These are now owned by overseas parent companies. There are also a number of smaller UK suppliers that operate in the field of industrial water treatment, including the power industry.
- There has been some loss of in-house capabilities within UK water treatment plant suppliers for power plant applications in comparison to historical competencies. Lack of business from the power market in recent years has meant that most companies have diversified into alternative market sectors in order to sustain business.
- Christ Kennicott and Elga Process Water are best placed amongst UK firms for new utility and industrial power plant contracts, with well established contacts with main contractors, proven expertise and partnerships and licensing agreements with other suppliers. Synergies with affiliated businesses within the parent company group can also provide benefits.
- The limited size and experience of the smaller UK suppliers is seen by main plant contractors as a commercial risk for large utility power projects. More success would be expected with small scale industrial power plant. For smaller UK firms to be utilised significantly in new power plant build, improved contacts with EPC contractors would need to be established and maintained.
- There is little UK RD&D activity in the field of industrial water treatment. RD&D is generally carried out overseas by the major water treatment plant suppliers. Most UK suppliers are reliant on technology transfer from equipment manufacturers.

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Dorr Oliver Eimco UK Ltd  
Dow Liquid Separations  
Elga Process Water (Veolia Water Systems Ltd)  
Environmental Water Systems (UK) Ltd  
Esmil Process Systems Ltd  
GE Infrastructure Water and Process Technologies  
Ionpure Technologies  
Hydranautics  
Memcor Ltd  
Purolite International Ltd  
Satec Ltd  
Siemens Power Generation  
ZENON Environmental (UK) Ltd



## APPENDIX A: EU Water Framework Directive Priority Substances

	Priority Substance (PS)	Priority Hazardous Substance (PHS) √ Identified (√) Subject to review
1	Alachlor	
2	Anthracene	(√)
3	Atrazine	(√)
4	Benzene	
5	Polybrominated diphenyl ethers	(√)
6	Cadmium	√
7	Short chain chlorinated paraffins	√
8	Chlorfenvinphos	
9	Chlorpyrifos	(√)
10	1,2-Dichloroethane	
11	Dichloromethane	
12	Di(2-ethylhexyl)phthalate (DEHP)	(√)
13	Diuron	(√)
14	Endosulfan	(√)
15	Fluoranthene <sup>1</sup>	
16	Hexachlorobenzene	√
17	Hexachlorobutadiene	√
18	Hexachlorocyclohexane (including Lindane)	√
19	Isoproturon	(√)
20	Lead	(√)
21	Mercury	√
22	Naphthalene	(√)
23	Nickel	
24	Nonylphenols	√
25	Octylphenols	(√)
26	Pentachlorobenzene	√
27	Pentachlorophenol	(√)
28	Polycyclic aromatic hydrocarbons	√
29	Simazine	(√)
30	Tributyltin compounds	√
31	Trichlorobenzenes	(√)
32	Trichloromethane (chloroform)	
33	Trifluralin	(√)

(1) Listed as an indicator of other, more dangerous, Polyaromatic Hydrocarbons

## APPENDIX B: Dangerous Substances Directive Lists

List I	List II (Inorganics)	List II (Organics)
Mercury	Arsenic	Benzene
Cadmium	Lead	Toluene
Trichloroethylene (TRI)	Chromium	Xylene
Tetrachloroethylene (PER)	Zinc	Naphthalene
1,2-dichloroethane (EDC)	Copper	Biphenyl
Chloroform	Nickel	1,1,1-Trichloroethane
Carbon tetrachloride (CTC)	Boron	1,1,2-Trichloroethane
Trichlorobenzenes (TCB)	Iron	2-Chlorophenol
Hexachlorobenzene (HCB)	Vanadium	2,4-Dichlorophenol
Hexachlorobutadiene (HCBd)	pH	2,4-D (ester and non-ester)
Hexachlorocyclohexane (HCH) (all isomers)		4-Chloro-3-methyl-phenol
Pentachlorophenol (PCP)		Chloronitrotoluenes
DDT (all isomers)		Atrazine and Simazine
Aldrin		Azinphos-methyl
Dieldrin		Bentazone
Endrin		Demetons
Isodrin		Dichlorvos
		Dimethoate
		Endosulfan
		Fenitrothion
		Linuron
		Malathion
		Mecoprop
		Mevinphos
		Omethoate
		Permethrin
		Trifluralin
		Triazaphos
		PCDSs
		Cyfluthrin
		Sulcofuron
		Flucofuron
		Tribuyltin
		Triphenyltin and derivatives

## APPENDIX C: Capabilities of Key Players in the Global Water Treatment Market

### Ion Exchange Resin Manufacturers

Company Name	Country of Origin	Website	Ultimate Parent Company and Country of Origin	Notes
Dow Liquid Separations	USA	<a href="http://www.dow.com/liquidseps/index.htm">www.dow.com/liquidseps/index.htm</a>	The Dow Chemical Company, USA	<ul style="list-style-type: none"> <li>• Manufacture and supply of DOWEX® ion exchange resins.</li> <li>• UPCORE trademark.</li> </ul>
Lanxess	Germany	<a href="http://www.lanxess.com">www.lanxess.com</a>		<ul style="list-style-type: none"> <li>• Manufacture and supply of Lewatit ion exchange resins.</li> <li>• Lanxess was formed as an independent company from Bayer AG in 2004.</li> </ul>
The Purolite Company	UK	<a href="http://www.purolite.com">www.purolite.com</a>		<ul style="list-style-type: none"> <li>• Manufacture and supply of Purolite ion exchange resins.</li> <li>• Puropack trademark.</li> </ul>
Rohm and Haas	USA	<a href="http://www.rohmhaas.com/ionexchange/index.htm">www.rohmhaas.com/ionexchange/index.htm</a>		<ul style="list-style-type: none"> <li>• Manufacture and supply of ion exchange resins and adsorbents for water treatment.</li> <li>• Amberlite, Amberjet, Ambersep and Amberpack trademarks.</li> </ul>

## Membrane Manufacturers

Company Name	Country of Origin	Website	Ultimate Parent Company and Country of Origin	Notes
Applied Membranes	USA	<a href="http://www.appliedmembranes.com">www.appliedmembranes.com</a>		<ul style="list-style-type: none"> <li>• Manufacture and supply of reverse osmosis, nanofiltration, ultrafiltration and microfiltration membranes.</li> </ul>
Dow Liquid Separations	USA	<a href="http://www.dow.com/liquidseps/index.htm">www.dow.com/liquidseps/index.htm</a>	The Dow Chemical Company, USA	<ul style="list-style-type: none"> <li>• Manufacture and supply of FILMTEC™ reverse osmosis and nanofiltration membranes.</li> </ul>
Electropure, Inc.	USA	<a href="http://www.electropure-inc.com">www.electropure-inc.com</a>		<ul style="list-style-type: none"> <li>• Electrodeionisation (EDI) products for OEM system integrators.</li> </ul>
Hydranautics	USA	<a href="http://www.membranes.com">www.membranes.com</a>	NittoDenko, Japan	<ul style="list-style-type: none"> <li>• Manufacture and supply of reverse osmosis, nanofiltration and ultrafiltration membranes.</li> </ul>
IonPure Technologies, Inc.	USA	<a href="http://www.ionpuretech.com">www.ionpuretech.com</a>	Siemens AG, Germany	<ul style="list-style-type: none"> <li>• Continuous Electrodeionisation (CEDI) products for OEM system integrators.</li> <li>• Part of USFilter (Siemens Industrial Solutions and Services Group).</li> </ul>
Koch Membrane Systems	USA	<a href="http://www.kochmembrane.com">www.kochmembrane.com</a>		<ul style="list-style-type: none"> <li>• Development and manufacture of membrane filtration systems, including reverse osmosis, microfiltration, nanofiltration and ultrafiltration.</li> </ul>
Toray Membrane	Japan	<a href="http://www.toray-membrane.com">www.toray-membrane.com</a>	Toray Group, Japan,	<ul style="list-style-type: none"> <li>• Manufacture and supply of reverse osmosis, nanofiltration, ultrafiltration and microfiltration membrane elements.</li> </ul>
TriSep Corp.	USA	<a href="http://www.trisep.com">www.trisep.com</a>		<ul style="list-style-type: none"> <li>• Manufacture and supply of reverse osmosis, nanofiltration, ultrafiltration and microfiltration membranes and associated support chemicals.</li> </ul>

## Water Treatment Plant Original Equipment Manufacturers

Company Name	Country of Origin	Website	Ultimate Parent Company and Country of Origin	Notes
Anderson Water Systems	Canada	www.awsl.com	SUEZ, France	<ul style="list-style-type: none"> <li>Design, engineering, manufacturing and commissioning of industrial water treatment systems, including reverse osmosis, electrodeionisation, ion exchange, degasification, clarification, and filtration technologies.</li> <li>Anderson Water Systems is part of the Ondeo group owned by Suez.</li> </ul>
Aquatech International Corp.	USA	www.aquatech.com		<ul style="list-style-type: none"> <li>Water and wastewater treatment systems, including raw water treatment, ion exchange, membrane systems, wastewater reuse/recycle, zero liquid discharge and desalination.</li> </ul>
Black & Veatch Corp.	USA	www.bv.com		<ul style="list-style-type: none"> <li>Water and wastewater treatment plant process engineering, contract management, design and construction, including clarification, filtration, membrane and ion exchange systems.</li> </ul>
Christ Water Technology Group	Switzerland	www.christwt.ch	BWT Best Water Technology Group, Austria	<ul style="list-style-type: none"> <li>Design, supply and construction of engineered water treatment systems for power plant and industrial water and wastewater treatment.</li> <li>Technologies include reverse osmosis, ion exchange, condensate polishing, electrodeionisation, evaporation, biological processes, flocculation and precipitation, and disinfection.</li> </ul>
Ecodyne Ltd.	Canada	www.ecodyne.com	The Marmon Group, Inc, USA	<ul style="list-style-type: none"> <li>Design and manufacture of water treatment equipment and systems, including deaerators, ion exchange, reverse osmosis systems and electrodeionisation technology.</li> </ul>
Eco-Tec, Inc.	Canada	www.eco-tec.com		<ul style="list-style-type: none"> <li>Design and manufacture of integrated water treatment systems, including demineralisation, filtration, reverse osmosis, condensate polishing and softening systems.</li> </ul>
Fisia Italimpianti	Italy	www.fisiait.com	IMPREGILO S.p.A., Italy	<ul style="list-style-type: none"> <li>Plant engineering contractor for desalination, wastewater and solid waste treatment.</li> </ul>

<b>Company Name</b>	<b>Country of Origin</b>	<b>Website</b>	<b>Ultimate Parent Company and Country of Origin</b>	<b>Notes</b>
GE Infrastructure Water & Process Technologies (GEI-W&PT)	USA	www.gewater.com	General Electric, USA	<ul style="list-style-type: none"> <li>• Global supplier of water, wastewater and process systems solutions, including design, installation, operation and maintenance of plant, and speciality chemical treatment programs and dosing systems.</li> <li>• Technologies offered include electrodeionisation, desalination, reverse osmosis, ultrafiltration, evaporation and crystallisation.</li> </ul>
GL&V - Groupe Laperrière & Verreault Inc.	Canada	25, des Forges Street Trois-Rivieres, G9A 6A7 +44-819-371-8265 www.glv.com		<ul style="list-style-type: none"> <li>• Water, wastewater and FGD scrubber blowdown treatment systems.</li> </ul>
Graver Water Systems, Inc.	USA	www.graver.com	The Marmon Group, Inc, USA	<ul style="list-style-type: none"> <li>• Design and manufacture of water and wastewater treatment equipment, including hot lime softening, boiler make-up, condensate polishing and cooling water treatment.</li> </ul>
IDE Technologies Ltd.	Israel	www.ide-tech.com		<ul style="list-style-type: none"> <li>• Development, design and installation of thermal and membrane desalination systems.</li> </ul>
Memcor Limited	Australia	www.usfilter.com	Siemens AG, Germany	<ul style="list-style-type: none"> <li>• Design and manufacture of microfiltration, ultrafiltration, nanofiltration and membrane bioreactors for water and wastewater treatment.</li> <li>• Part of USFilter (Siemens Industrial Solutions and Services Group).</li> </ul>
NORIT Membrane Technology	Netherlands	www.noritmt.com	Norit B.V., Netherlands	<ul style="list-style-type: none"> <li>• Design, manufacture, supply and maintenance of stand alone ultrafiltration systems.</li> </ul>
Omexell, Inc.	USA	www.omexell.com	Omex Group, USA	<ul style="list-style-type: none"> <li>• Design, engineering, manufacturing, installation, and service of membrane technology equipment, including ultrafiltration, reverse osmosis and electrodeionisation.</li> </ul>
Ondeo Industrial Solutions	France	www.ondeo-is.com	SUEZ, France	<ul style="list-style-type: none"> <li>• Process water purification, waste water and sludge treatment improvements across the industrial water cycle.</li> <li>• Design and build capability and equipment range includes basic clarification, membrane technologies such as reverse osmosis and electrodeionisation, ion exchange processes and filtration.</li> </ul>

<b>Company Name</b>	<b>Country of Origin</b>	<b>Website</b>	<b>Ultimate Parent Company and Country of Origin</b>	<b>Notes</b>
Organo Corporation	Japan	www.organo.co.jp		<ul style="list-style-type: none"> <li>• Global supplier of water and wastewater treatment plant, including turnkey contracting, plant operation and maintenance, and project management.</li> <li>• Technologies offered include conventional filtration, ion exchange, reverse osmosis, ultrafiltration and microfiltration.</li> </ul>
Pall Corporation	USA	www.pall.com		<ul style="list-style-type: none"> <li>• Design, production, and supply of membranes, filtration devices, and separation systems, including ultrafiltration and microfiltration water treatment systems.</li> </ul>
USFilter	USA	www.usfilter.com	Siemens AG, Germany	<ul style="list-style-type: none"> <li>• Global provider of commercial and industrial water and wastewater treatment systems, including water treatment for cooling tower make-up or boiler feed, reduced or zero waste discharge and FGD wastewater treatment.</li> </ul>
Veolia Water Systems Ltd.	France	www.veoliawatersystems.com	Veolia Water, France	<ul style="list-style-type: none"> <li>• Design, engineering, project management and maintenance for turnkey plants and industrial water and wastewater treatment worldwide.</li> <li>• Technologies include electrodeionisation, reverse osmosis, microfiltration, ion exchange demineralisation, desalination, clarifiers.</li> <li>• Support chemicals and mobile water treatment plant are also offered.</li> </ul>
ZENON Environmental Services	Canada	www.zenonenv.com		<ul style="list-style-type: none"> <li>• Membrane based water and wastewater technology for industrial and power markets, including ultrafiltration, reverse osmosis, ion exchange and ancillary equipment.</li> </ul>

## UV and Ozone Disinfection

<b>Company Name</b>	<b>Country of Origin</b>	<b>Website</b>	<b>Ultimate Parent Company and Country of Origin</b>	<b>Notes</b>
Ozonia	France	www.ozonia.com		<ul style="list-style-type: none"> <li>• Ozone and UV light technology for oxidation and disinfection water treatment applications.</li> </ul>
Trojan Technologies Inc.	Canada	www.trojanuv.com	Danaher Corp., USA	<ul style="list-style-type: none"> <li>• Design and manufacture of ultraviolet disinfection systems for wastewater and industrial applications.</li> </ul>
WEDECO Ag Water Technology	Germany	www.wedeco.com	ITT Industries Inc., USA	<ul style="list-style-type: none"> <li>• UV and ozone water treatment technologies.</li> </ul>



## APPENDIX D: Capabilities of UK Water Treatment Plant Suppliers

Company Name	Address	Website	Ultimate Parent Company and Country of Origin	Notes
ACWA Services Ltd.	ACWa House Keighley Road, Skipton North Yorkshire BD23 2UE +44 (0)1756 794 794 acwa@acwa.co.uk	www.acwa.co.uk	Consolidated Contractors Company, Greece	<ul style="list-style-type: none"> <li>• Design and construction of water, effluent and air purification systems.</li> </ul>
Alpheus Environmental Ltd	49a Bromham Road Bedford, MK40 2AA +44 (0)1234 686100 enquiries@alpheus.co.uk	www.alpheus.co.uk	Anglian Water Group plc, UK	<ul style="list-style-type: none"> <li>• Service company offering outsourced operation and maintenance of water and wastewater facilities to customers within the UK.</li> </ul>
AWE Anderson Water Equipment	Cardiff Bay Business Centre Lewis Road, Ocean Park Cardiff, CF24 5EL +44 (0)29 2049 2848 water@aweltd.co.uk	www.aweltd.co.uk		<ul style="list-style-type: none"> <li>• Design and manufacture of bespoke water purification systems for industrial customers.</li> </ul>
Christ Kennicott Water Technology Ltd	Kennicott House Well Lane, Wednesfield Wolverhampton +44 (0)1902 721212 information@christwt.co.uk	www.christwt.co.uk	BWT Best Water Technology Group, Austria	<ul style="list-style-type: none"> <li>• Design and manufacture of power plant and industrial water and wastewater treatment systems.</li> </ul>
Derwent Water Systems Ltd.	Unit 6, Brookfield Way Matlock, Derbyshire DE4 5ND +44 (0)1629 55617 derwentwater@clara.net	www.derwentwatersystems.co.uk		<ul style="list-style-type: none"> <li>• Manufacture and supply of water treatment plant.</li> </ul>
Dorr Oliver Elimco UK Ltd	Swift House, Cosford Lane Rugby, CV21 1QN Warwickshire +44 (0)1788 555777	www.dorrolivereimco.co.uk	Groupe Laperrière & Verreault Inc., Canada	<ul style="list-style-type: none"> <li>• Large scale water, wastewater and scrubber blowdown treatment systems.</li> </ul>

<b>Company Name</b>	<b>Address</b>	<b>Website</b>	<b>Ultimate Parent Company and Country of Origin</b>	<b>Notes</b>
Ecolochem International Ltd	HydroHouse Newcombe Way Orton Southgate Peterborough, PE2 6SE +44 (0)1733 394555	www.ecolocheminternational.com	General Electric, USA	<ul style="list-style-type: none"> <li>• Mobile emergency equipment and outsourced industrial and power plant water treatment services.</li> </ul>
Esmil Process Systems, Ltd.	The Loft 30 Abbey Barn Road High Wycombe Bucks HP11 1RW +44 (0)1494 526 155 info@esmil.co.uk	www.esmil.co.uk		<ul style="list-style-type: none"> <li>• Industrial water treatment solutions involving membrane technology for process systems and wastewater treatment and recovery.</li> </ul>
EWS Environmental Water Systems (UK) Ltd.	Charwell House Cheddar Business Park Wedmore Road Cheddar Somerset BS27 3EB enquires@reverseosmosis.co.uk	www.environmentalwatersystems.co.uk		<ul style="list-style-type: none"> <li>• Water purification, water recovery and process filtration.</li> </ul>
Elga Process Water (Veolia Water Systems Ltd.)	Springbank House High Street, Lane End High Wycombe Bucks, HP14 3JH +44 (0)1494 887 700	www.veoliawatersystems.co.uk	Veolia Water, France	<ul style="list-style-type: none"> <li>• Engineering, design and build schemes for all aspects of industrial water and wastewater treatment, including mobile water purification plant services.</li> </ul>
Memcor Limited	Derby Road Wirksworth Derbyshire DE4 4BG +44 (0)1629 823811 info@memcor.co.uk	www.usfilter.com/water/municipal/membranes	Siemens AG, Germany	<ul style="list-style-type: none"> <li>• Design and manufacture of microfiltration, ultrafiltration, nanofiltration and membrane bioreactors for water and wastewater treatment.</li> </ul>
PURAC Ltd.	PURAC House Birmingham Road, Kidderminster Worcestershire, DY10 2SH +44 (0)1562 820010 admin@purac.co.uk	www.purac.net	Anglian Water Group plc, UK	<ul style="list-style-type: none"> <li>• Process engineering and contracting group for municipal and industrial water and wastewater treatment.</li> </ul>

<b>Company Name</b>	<b>Address</b>	<b>Website</b>	<b>Ultimate Parent Company and Country of Origin</b>	<b>Notes</b>
Satec Ltd.	The Street Englefield, Reading Berkshire, RG7 5ES +44 (0)118 964 9006 info@satec.co.uk	www.satec.co.uk		<ul style="list-style-type: none"> <li>• Water, waste water, sewage and effluent treatment, including plant servicing and spares supply.</li> </ul>
Sterling Hydrotech	Freshwaters, Park Road Holmewood Chesterfield, S42 5UY Derbyshire +44 (0)1246 857000 enquiries@sterling-hydrotech.co.uk	www.sterling-hydrotech.co.uk		<ul style="list-style-type: none"> <li>• Water treatment plant manufacture and service.</li> </ul>
ZENON Environmental (UK) Ltd	Bullhouse Mill, Lee Lane Millhouse Green Sheffield, South Yorkshire S36 9NN +44 (0)1226 760600	www.zenon.com		<ul style="list-style-type: none"> <li>• Membrane based water and wastewater technology for industrial and power markets, including ultrafiltration, reverse osmosis, ion exchange and ancillary equipment.</li> </ul>