Handbook of Water Purification

Editor: Walter Lorch

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Editors and contributors

The editor

Walter F. Lorch has been active in the world of water for thirty years. His invention—the cartridge-type deionizer—in 1955 has superseded the classical process of distillation and has brought to research, medicine, and industry ultra-pure water at tap speed. His original concept of harnessing ion exchangers in this form has outdated heat distillation and saved the community inestimable amounts of energy, time, and money—world wide.

An electrical engineer by training, he joined the Royal Electrical and Mechanical Engineers in the 6th Airborne Division in 1940. Emerging into peace with the rank of Sergeant, he returned to work in the field of water treatment. He designed the pilot units used by Saunders which lead to the acceptance by the Pharmacopoeia Commission of deionized water in place of distilled water. His designs for ion exchange and later for reverse osmosis systems have revolutionized purified water production in the pharmaceutical industry.

He was first—in 1958—to recognize the importance of recycling water rather than wasting it and produced the first recirculator for water reclamation. His design philosophy has since been adopted throughout the electronic industry, resulting in phenomenal savings of water and energy. Lorch has published innumerable papers and regards water purification as a way of life. He is a Member of the Worshipful Society of Apothecaries of London, and a Freeman of the City of London. His motto: 'simplicity of design'.

Much of the earnings of his family business—Elga Products Ltd—go to the Lorch Foundation, whose aim is to encourage original thought and common sense. In 1980 the Foundation became a charitable Trust and Lorch established the world's first School of Water Sciences at their Seminar Centre in Buckinghamshire, UK. Courses range from two-day sessions for Commissioning Engineers to Summer Courses for postgraduates. Programmed instruction courses on water technology are available in several languages with emphasis on the Third World.

Author of Chapter 4, coauthor of Chapter 7, and editor of Part Four.

Felix Franks, BSc, PhD, DSc

Franks gained his early experience both in the polymer and food industry and as senior lecturer in Physical Chemistry at the University of Bradford. His present positions include Special Professor of Biophysics at the University of Nottingham and Senior Research Fellow in the Department of Botany, University of Cambridge, where his current research interest concerns the low-temperature preservation of plant tissue, biochemistry at subzero temperatures, and the mechanisms of frost and chill resistance.

Professor Franks has held several academic posts abroad including visiting professorships at the University of Waterloo, Canada, the Australian National University, Canberra, and the University of Pittsburgh, Pa. He has written extensively on various aspects of water and is editor and part-author of *Water—A Comprehensive Treatise* in six volumes.

Author of Chapter 1.

Richard Hill, BSc (ChemEng), CEng, MIChemE, MIWE

Hill read Chemical Engineering at the University of Leeds and discovered an interest in water through a series of holiday jobs in the Research and Development Division of William Boby Ltd, where he worked under George Solt (author of Chapter 9). On graduating he first joined the Water Research Centre, UK, where he investigated the economics of ammonia removal from river water for the production of potable water. Then followed a period in industry, leading to the position of Projects Manager for the Permutit Standard Plant Division. He now works in a similar capacity for Dewplan (WT) Ltd, where he is in charge of the design of water treatment plant.

Coauthor of Chapter 7.

William Douglas Meredith, TEng (CEI), SEng, MInstM, MISM, AMBIM, MIMRA

Meredith studied Chemical Engineering at Glamorgan College of Technology and subsequently gained an interest in instrumentation during service in the Royal Air Force as an instructor to Air Radar Fitters. After three years as Development Engineer on the first UK factory-built computer of Standard Telephones Laboratories, he joined First Cleveland Instruments Ltd, developing mass flowmeters. Since 1960 he has worked for Electronic Instruments Ltd, now part of the Brown Boveri Kent Group, in a marketing technical capacity on instrumentation allied to process control and, in particular, to water and waste water treatment.

Author of Chapter 11.

Hermann W. Pohland, Dr rer Nat

Pohland graduated in 1959 as a Diploma-Chemiker (Organic Chemistry) from the University of Bonn. His synthetic work in the field of isothiazoles led to the Dr rer. Nat. in 1961. After a period as Assistant Professor (Organic Analysis) at the University of Bonn and a year at the Banting and Best Institute of the University of Toronto (Karl Duisberg fellow, 1961) as a Research Associate (Synthesis of Phospholipids) he joined E. I. Du Pont de Nemours and Co., USA, in 1962. His industrial career led him through assignments in Research and Development, Manufacturing and Marketing, to his current position of Technical Consultant for the Permasep Products Division (reverse osmosis membranes).

Pohland is a member of the American Chemical Society, the American Association of Textile Chemists and Colorists, and the Gesellschaft Deutscher Chemiker; he holds several patents and has published in the fields of textile dyes as well as reverse osmosis.

Author of Chapter 8.

Derek B. Purchas, NBc., DipChem, CEng, MIChemE

Purchas graduated in 1949 from London University in Chemistry and Physics, with a post-graduate diploma in Chemical Engineering from University College, London. His early career included extensive experience in research and development as well as technical sales with companies prominent in the separation equipment field. Since 1965 he has practised privately as a consultant chemical engineer, working for both industry and government departments.

He is the author of *Industrial Filtration of Liquids*, published originally in 1967 and now being published for the third time. He is also editor and part-author of *Solid/Liquid Separation Scale-Up*, published in 1977, which presented the first authoritative guidance on how to size a wide range of equipment including filters, centrifuges, and gravitational devices. He is a regular contributor to *Filtration and Separation* and Honorary Editor of *The Chemical Engineer*.

Author of Chapter 5.

Louis C. H. Ross, CEng, MIMechE

After an engineering apprenticeship and mechanical engineering studies at the Leeds College of Technology, Ross spent his working life in industry. For the past twenty years his work as a mechanical engineer in semi-conductor manufacturing has involved him in the development of semi-conductor processes and equipment, particularly while at Mullards, Southampton. Most recently he has worked on the specification, development, and design of high purity water conveyance and recirculation associated with semi-conductor production. He is now a consultant engineer and photographer.

Author of Chapter 12.

Leonard Saunders, BSc, PhD, DSc

Saunders graduated in Chemistry from the University of London in 1937. He gained a Ph.D. in 1941 for Physical Chemistry research work on adsorption at a liquid interface and his D.Sc. in 1958 for research in Physical Chemistry. His early career included an Assistant Lectureship in Chemistry at the University of Sheffield and research with the British Aluminium Co. on surface and colloid chemistry. In 1949 he was made Senior Lecturer at The School of Pharmacy, University of London, and subsequently Reader. He is currently Professor.

Saunders has written several textbooks including *Mathematics and Statistics for Pharmacy*, *Principles of Physical Chemistry for Biology and Pharmacy*, and *The Adsorption and Distribution of Drugs*. Many of his published papers following research have had far-reaching consequences in the world of water purification. These include: 'Demineralized water for pharmaceutical purposes', *Journal of Pharmaceutical Pharmacology*, **6**, 1014, 1954, which led to the acceptance by the British Pharmacopoeia of ion exchange as a method for preparing purified water, and 'Sustained release of drugs from ion exchange resins', *Journal of Pharmaceutical Pharmacology*, **8**, 975, 1956, which resulted in the development of sustained release preparations. He has published many papers on ion exchange, phospholipids, water purification, and pharmacokinetics.

Author of Chapters 3 and 6.

Günther O. Schenck, Professor Dr.rer.nat.habil., Dipl.-Chem.

Schenck obtained his degree 'Summa cum laude' at the Universität Halle/Saale and gained his early experience in photochemistry at the Chemisches Institut, Universität Halle/Salle. From 1946–50 Schenck worked on his own account as a consultant in photochemistry. From 1950–59 he was Professor at the Universität Göttingen and Director of the Organisch-Chemischen Institut. In 1957 Schenck joined the Max-Planck Institut to build up their Department of

Radiation Chemistry and he is now the Director of the Max-Planck Institut für Strahlenchemie. He was made an Honorary Fellow of the Royal Society of Edinburgh and became an Honorary Member of the European Photochemistry Association. He was Visiting Professor at the University of Salford, UK (1974–75), President of the Comité International de Photobiologie in 1975, and an Honorary Member of the Executive Committee of the Association Internationale de Photobiologie in 1980. Schenck has written many papers in the field of photochemistry, particularly for the UV disinfection of water, and holds several patents for the photochemical preparation of components to render them photosensitive to sunlight.

Author of Chapter 10.

George Solt, BSc (Hons), CEng, FIChemE, FRIC

Solt is a chemical engineer by training, who has spent most of his career in the development of various aspects of ion exchange. This includes many years pioneering desalting equipment using ion exchange membranes. He has acted as consultant to United Nations desalination projects and was a member of the Department of the Environment's Central Advisory Water Committee whose report led to the formation of Britain's Regional Water Authorities. In 1970 he was awarded a two year fellowship as Visiting Professor to University College, London, where he remains an Honorary Research Fellow and Lecturer. He is Research and Development Director of Dewplan (WT) Ltd, High Wycombe, UK, and currently seconded to The School of Water Sciences, The Lorch Foundation, UK, as Director of Studies.

Author of Chapters 2 and 9.

Barry J. Weissman, MS, BChe

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Author of Section 5, Chapter 5.

T. Douglas Whittet, CBE, HonDSc(Bath and Aston), BSc, PhD, FPS, CChem, FRIC, DBA

Whittet qualified as a pharmaceutical chemist at Sunderland Polytechnic in 1938 and in 1943 was made Chief Pharmacist and Lecturer in Pharmacy at the Charing Cross Hospital. He gained his B.Sc. (1953) and his Ph.D. (1958) through research in the field of pyrogens, when he also did research into drug stability and formulation. He investigated the effects of ion exchange resins on pyrogens and tested the effect of ionizing radiations on pyrogens.

In 1965 Whittet was appointed Deputy Chief Pharmacist, Ministry of Health, UK, and became Chief Pharmacist in 1967. He served on the European Pharmacopoeia Commission, the Council of Europe Pharmaceutical Committee, and in 1967–68 led the United Kingdom delegation which negotiated the European Free Trade Association Convention on the Mutual Recognition of Pharmaceutical Inspections. In 1980 Whittet was elected a Fellow of University College, London, and an Honorary Fellow of Sunderland Polytechnic. His hobbies include the history of medicine and pharmacy.

Author of Chapter 13.

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Preface

Researching, collating, and writing this book has been a revelation. I am neither a scientist nor professionally qualified and could not have started a task with a more uneasy mind. But, working in the world of water purification for thirty years has evolved, formed, and fortified the concept for this handbook, a word which the Oxford Dictionary defines as 'short treatise, manual, guide-book'. This is a guide for the *users* of purified water. It is written by a team of experts in their own field of water knowledge and presented in a language essentially free from professional jargon. Thousands of volumes have been written on water management, on the production of drinking water, and on the preparation of cooling water for industry. Indeed, the largest amount of treated water is used for these purposes and the extensive literature is written by the specialist for the specialists who install and operate large water treatment systems.

There remains a large amount of know-how which relates to the purification of water for research, industry, and medicine. In chemical processing, the electronic industry, for boiler feed, humidification, and metal finishing, in pharmaceutical manufacture, and hospitals purified water is required in ever-increasing volumes and of a quality which approaches that of absolute water. The diversity of use for purified water and the multitude of sophisticated systems in operation is far greater than the relatively simple processes employed for public water supplies.

Today's life, our health care, research, and industry rely on the unfailing availability of purified water. Society cannot function without it. Despite the dissimilarity of options, two common factors emerge:

1. Most tap water purification systems are operated by technical personnel who have no specialized training or knowledge of water treatment.
2. The quality of the purified water is critical for the success of process or operation.

The major part of this handbook is therefore devoted to the processes and systems designed to convert potable water to purified water of a predetermined specification. It presents not just the theory and technology of the available purification processes: the handbook will give to reader the quantitative measurements essential to express the characteristics of the raw material—tap water— and to specify clearly and without compromise the expected product--purified water. In this way the treatment processes will evolve logically from these parameters.

In areas where public water supplies are inadequate or non-existent, raw water sources will have to be upgraded to drinking water standards. The preliminary treatment which must be applied to achieve this is outside the scope of the handbook, but is touched on briefly to produce a more complete understanding of the process chain from raw water to absolute water.

How to use this book

If you read nothing else please read this.
If you intend to read some chapters please read this *first*.

1. This book defines

1.1. Water purification. As the removal of suspended and dissolved matter and colloids, gases, and biological contaminants.

1.2. Units of measurement. As SI or SI-derived units. Traditional units used to define specialized parameters have been retained in some cases for the sake of clear understanding. Conversion tables are given in Appendix A.

1.3. Process cost. Because money values change rapidly and are utterly meaningless on an international scale, economical considerations are expressed in, or related to, power (energy/time) or energy (work/heat) factors from which readers can readily calculate their own process cost.

2. This book discusses

2.1. The properties of water
2.2. The terms in which the quality of natural and purified water is expressed
2.3. Every practical process of water purification
2.4. Every practical method of measuring or controlling water quality
2.5. How purified water is conveyed and stored
2.6. Briefly—in outline only—the principles of production of drinking water from fresh water or the sea

3. This book pinpoints your purification task, problem or question by

3.1. Reference to Part One, Chapters 2 'Natural Waters' and 4 'Water Quality', leading to
3.2. Choice of purification process and sytem in Part Two, leading to
3.3. Examples and case histories of purified water production in Parts Three and Four

4. This book does not include

4.1. Water conditioning and chemical sterilization
4.2. Effluent or waste water treatment
4.3. Legislation

5. The following reference books supplement this handbook:

Blake, *Water Treatment for HVAC and Potable Water Systems*, McGraw-Hill, 1980.
Degrémont, *Water Treatment Handbook*, Wiley, 1979.
Nalco, *The Nalco Water Handbook*, McGraw-Hill, 1979.

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Part one

The properties of water

1. The hydrologic cycle: turnover, distribution, and utilization of water

F. FRANKS

Its universality . . . its vastness in the ocean . . . the restlessness of its waves . . . its hydrostatic quiescence in calm . . . its sterility in the circumpolar ice-cap . . . its preponderance of 3 : 1 over tl dry land of the globe . . . its slow erosions of peninsulas . . . the simplicity of its composition . . . metamorphoses as vapour, mist, cloud, rain, sleet, snow, hail . . . its submarine fauna and flora, numerically, if not literally, the inhabitants of the globe . . . its ubiquity as constituting 90% of the human body . . . .

James Joyce

It is a truism that water existed on this planet long before life first evolved and that all the complex chemical processes involved in the development and maintenance of living organisms are therefore sensitively attuned to the physical properties of liquid water. Indeed, Nobel laureate Szent-György has called water 'the matrix of life'. The interplay of water and life can be considered at several different stages. At the basic level the electronic structure of the H_2O molecule is responsible for the physical properties of liquid water, most of which are quite atypical, as judged by the usual chemical and physical standards. Next we can consider water as one of the necessary molecular reactants in biological synthesis and metabolism. At a yet more complex level, water is the carrier fluid which serves to distribute nutrients and other essential chemicals throughout the organism. Finally, water forms the natural habitat of many forms of life. Those plants and animals which have, during the course of evolution, managed to adapt themselves to an existence out of water have paid a heavy price in terms of energy expenditure. They have had to develop complex machinery to control their water supply, purification, and turnover.

It is precisely because water is one of our most valuable resources that so much effort is now devoted to its management, and yet its all-important role in the maintenance of life is not generally appreciated, or is taken for granted. The extreme sensitivity of most biochemical processes to the physical properties of water is strikingly illustrated by the consequences of replacing 'ordinary' water by heavy water, D_2O. This substance, physically and chemically almost identical to H_2O, structurally only differs from it by the weight of the hydrogen atoms. Nevertheless, it acts as a poison to all higher forms of life in that it will not support growth.

The complex interactions between water and life processes are therefore fundamental to our need for supplies of pure potable water. Because water acts as 'universal solvent', the removal of dissolved substances is not always easy. Some manufacturing processes or medical application require water of even higher standards of purity, where the need for the removal of minute traces of organic and inorganic materials presents severe problems. To obtain an appreciation of the universal solvent action of water it is only necessary to study the list of elements present in solution in sea water; these range from chlorine (19 000 ppm) and sodium (10 500 ppm) at the high end of the concentration scale to mercury, silver, bismuth, and gold at 0·001 ppm levels. Even those elements whose solubilities are close to the detection limit, e.g., chromium, zirconium, and platinum, can be found in marine organisms, and must therefore be present in sea water.

1.1 History of the hydrosphere

The origin of water in the atmosphere and its eventual condensation on the earth's surface to form the hydrosphere are still subject to speculation. Certainly the total amount of water which now exists on earth could not be accommodated in the atmosphere, *as it now exists*. There are in fact clear indications that in prehistoric times profound changes must have occurred in the interactions between the atmosphere and the hydrosphere. Such changes are indicated, for instance, by rock erosion, the deposition of certain types of sediment, and the impressions of rain drops and wave ripples in rock formations.

Oxygen probably first appeared in the atmosphere as a result of the dissociation of water vapour by ultraviolet radiation. Small amounts of carbon dioxide may have originated from the erosion of minerals by weak carbonic acid. This was then converted to oxygen by the photosynthesis of plants. Rough calculations indicate that the present annual oxygen production by plants is 10^{11} tonnes (t), 99 per cent of which is required by animals for the metabolic oxidation of food. A normal human adult requires 500 l of oxygen every day. In connection with the magnitude of water turnover it is also of interest that photosynthesis by plants requires 10^{11} t of water annually.

Of the total oxygen generated, only 0·000 44 per cent remains in the atmosphere and, of this, 90 per cent is required for the oxidative erosion of minerals. Thus, about 5×10^7 kg of oxygen remains annually for the enrichment of the atmosphere. From a study of the growth of plant and animal life it is possible to construct a curve of the increase in atmospheric oxygen from a zero in the Precambrian age—1·5 billion years ago—until the present day. A dramatic upturn took place about 525 million years ago, but fossil remains indicate that even at that time life had already existed for some 3 billion years. If we assume that even the simplest forms of life required water for their development, we must conclude that water already existed on and around the earth long before that time. Since the prevailing temperature probably lay in the range 75–90°C, the distribution of water between atmosphere and hydrosphere and the forms of primitive life which it could support differed radically from the present-day situation. Dramatic redistributions of water must have occurred at various periods, with the oceans developing fairly late; e.g., the Atlantic Ocean is less than 200 million years old.

1.1.1 Oceans—reservoirs of water and energy

Although this book is not primarily concerned with the oceans as a source of fresh water, in terms of the hydrosphere they not only constitute our most important reservoir of water but also have a profound influence on climatic conditions, and therefore on precipitation. Because of the abnormally high specific heat of water, the oceans act as vast energy reservoirs; the warm currents lose this energy as heat to the surroundings, thus ensuring a stable, temperate climate. The scale of this energy transfer is hard to conceive: the heat lost by the Gulf Stream to the atmosphere over North-West Europe amounts to 4×10^{15} kJ/h, equivalent to the combustion of 40 million t of coal.

The oceans are also rich in mineral wealth and constitute the habitat of a large part of our potential food reserves. The scientific disciplines of physical and chemical oceanography and marine biology are still in their infancy and we can expect to witness important developments.

1.2 The hydrologic cycle

The continuous circulation of water by evaporation from the hydrosphere to the atmosphere and its subsequent precipitation back to the hydrosphere is referred to as the hydrologic cycle (see Fig. 1.1). The total water content of the atmosphere is 5×10^9 a ft† (6×10^8 ha m). Since the total annual precipitation is 183×10^9 a ft (225×10^8 ha m), the water in the atmosphere is turned over 37 times every year. This level of precipitation is equivalent to a water depth of 0·5 m averaged over the earth's surface.

Although the hydrologic cycle is a continuum, its usual description begins with the oceans, which cover 71 per cent of the earth's surface. Water evaporates into the atmosphere due to the heat of the sun. Normally the water vapour is invisible, but under certain conditions of supersaturation it forms clouds which are metastable. Under the influence of certain changes in temperature and/or pressure, the moisture condenses and returns to earth in the form of rain, hail, sleet, or snow—collectively referred to as water of meteoric origin.

1.2.1 Precipitation

To talk about an average annual 0·5 m of precipitation is misleading, because the actual distribution over the earth's surface is quite non-uniform and irregular in time as well as in space. Thus, the United States has an annual rainfall of about 0·76 m, but this again is very unevenly distributed. Most of the precipitated water returns directly to the oceans; the remainder falls on land as a result of one of three processes involving the precipitation from warm, moisture-laden air:

(a) *Cyclonic.* The warm air mass, either stationary or in horizontal motion, encounters a cold air mass.
(b) *Convectional.* An air mass, receiving heat and water vapour at the earth's surface, cools as it rises vertically.
(c) *In mountain regions.* A moving warm air mass is forced to rise and lose heat when it encounters a mountain barrier.

Meteoric water falls irregularly with respect to geographical location, with coastal areas receiving more. In the Northern Hemisphere the prevailing winds are westerly, so that the western slopes of mountain ranges generally receive adequate precipitation. As the air mass

† The orders of magnitude involved in water circulation on a global scale are so vast that they are difficult to appreciate. Probably the unit of the acre-foot most graphically describes the enormous quantities of water involved. The acre-foot is the volume which will cover an area of 1 a to a depth of 1 ft:

$$1 \text{ a ft} = 1223 \text{ m}^3 = 43\,560 \text{ ft}^3 = 330\,000 \text{ gal}$$

$$1 \text{ ha m} = 10\,000 \text{ m}^3$$