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John B Durkee II

Cleaning with Solvents

Science and Technology

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Cleaning with Solvents: Science and Technology

Preface

In many shops into and through the early 1990s, solvent cleaning was done using 1,1,1-trichloroethane (TCA) or 'Freon' (CFC-113), with little control of emissions. It was then discovered that when emitted these solvents catalyzed the deterioration of the stratospheric ozone layer above Earth, and their manufacture was banned per the Montreal Protocol.

Two decades later, concern lingers about the safety, health, and environmental (SHE) aspects of using some of the replacement solvents to clean surfaces of articles.

This book was written to address those concerns using straightforward science, experienced engineering, and an understanding of US regulations – without regard for political correctness.

In the early 1990s, coffee cans were often used as solvent storage tanks. Paint brushes acted as cleaning machines. The emission control device was the open air.

Two decades later, solvent cleaning is done with and in machines designed to replace the coffee can with a condensation system operating under vacuum. Both liquid and vapor spray devices have replaced the paintbrush. And the open air has been replaced with a reusable bed of activated carbon adsorbent. These machines can be complex and very expensive.

This book was created to dissolve that complexity by means of straightforward explanations coordinated with simple illustrations and supplemented by informative footnotes/endnotes.

In the early 1990s, a pound of solvent could be bought for the price of a gallon of gasoline. Two decades later, users experience "sticker shock" upon learning that the cost of filling an empty solvent cleaning machine can approximate the price of a good used car.

This book was created to explain that when the cost of filling a cleaning machine is amortized over the many parts cleaned by it, the cost of the solvent needed to fill it should be negligible, and that the major cost of solvent cleaning is the cost of compliance with environmental regulations if the solvent is not adequately retained within the cleaning machine.

Despite advances in written and electronic communications, I believe that verbal communication is still how most technical information about cleaning technology – at any level, gross, precision, or critical – is transmitted. Too often, technology transfer through publication of scientific papers isn't intended to educate, but to impress.

In the 1980s, I was assigned to develop and manage new cleaning technology for a large chemical company. I learned about the technology through conversations, with fellow professionals, suppliers, customers, operators and technicians, anyone. And, of course, I learned by doing! There were no academic offerings, no books, no trade magazines or professional journals. My cohorts reported similar experiences.

Preface

As a consultant, I found my clients had primarily learned from suppliers[1]. As someone providing training in cleaning technology, I found the previous experience of my students originated from the same source and methods as had my clients: chiefly, verbal contact with suppliers. Essentially, this technology transfer was done as is information shared among friends on Facebook – by personal contact.

Is this how are we going to train future practitioners of industrial cleaning?

This book is an answer to that question. The answer is NO!

[1] Some feel there is something inherently wrong about learning from suppliers. I see the situation as a bargain. On the one hand, suppliers know their technology and the pitfalls of its use better than anyone, and should have the capability to communicate it users. On the other hand, their point of view isn't, and shouldn't be, balanced and open about alternatives. On the third hand, suppliers know applications; from where is one to learn of basic theory?

Acknowledgments

A book may bear the name of a single author on its spine. But no published book – especially this one – is the product of just one person.

The genesis of this book was a request in 2001 to produce a chapter about either aqueous or solvent cleaning for a book being edited by my friends Rajiv Kohli, PhD and Kash Mittal, PhD for the publisher William Andrew. That request produced nothing intended. But the background technology needed for all cleaning work was produced in 2006 as the volume *Management of Industrial Cleaning Technology and Processes* (ISBN: 978-0080448886). In 2007, the old request was honored by the preparation of material about solvent cleaning published as Chapter 15 in *Developments in Surface Contamination and Cleaning – Fundamentals and Applied Aspects* (ISBN: 978-0815515555). To this author, it was evident that the one chapter was but a down payment on a charter to provide a full explanation of all aspects of solvent cleaning. It was also evident that global interest in safe, environmentally responsible, simple, and reliable solvent cleaning technology was growing. This book is an outcome of those beliefs.

My chief critic, advisor, and reviewer of this book was and is Steven Abbott, Ph.D., University of Leeds, UK. In no small measure is the quality inherent in this book due to his help; the defects are my responsibility. His unique ability to review and suggest revisions to the chemistry science I am trying to communicate and simultaneously be rigorous on grammar has never been equaled.

Two of the giants upon whose shoulders I stand as author are Charles Hansen, Ph.D. who answered innumerable questions over several years with uncommon courtesy and who led me to Laurie Williams and to Steven Abbott; and William P. L. (Bill) Carter, Ph.D., The University of California, Riverside, who gave me full and detailed criticism of the chapter on VOC chemistry.

Friends, advisors, teachers, and reviewers included Bob Benedetti, National Fire Protection Association, who as in 2006 reviewed my writing on management of flammability; Art Gillman, Unique Equipment; Joe McChesney, Control System Designs LLC; Howard Siegerman, Ph.D., formerly of Texwipe ITW, who reviewed the chapter on wipe cleaning; and Laurie Williams, Ph.D., who back in 2004 taught me about the thermodynamics of Hansen Solubility Parameters. Your support was needed and is appreciated.

Supporters, teachers, and advisors from whom I have benefitted include Edward Kallis, Vapor Engineering; Ken Kikta, Carbtrol; Peter Gerhard, formerly of Serec; Don Gray, Ph.D., Vacuum Processing Systems; Troy Hurley, Finish Thompson; the late Bill Johnson, US EPA; Ken Schaeffer, Carbon Resources; Steve Risotto, American Chemistry Council; David Sanders, US EPA; Margaret Shepherd, Ph.D., US EPA; Joe Schuttert, Vacuum Processing Systems; Darren Williams, Ph.D., Sam Houston State University; and Guy Vereeke, Ph.D., of IMEC.

The production of this book was complicated because of the sheer mass and complexity of material produced. Thanks to Matthew Deans, Senior Publisher, Elsevier Science & Technology Books, who exhibited the inordinate patience needed for me to complete this research and write about it, and then to enable its printing in color; David Jackson, Associate Acquisitions Editor Elsevier, who provided wise counsel every time there was a choice to be made; Pauline Wilkinson, Project Manager of technical books Elsevier, who made insoluble production problems disappear with dispatch; and John Hutchison esteemed proofing person, who found and corrected a seemingly endless stream of errors that were formerly unknown to all. And thanks to Karen Mosman of Syllaba who guided me in organizing all of the above material so that it might best serve the interest of readers. It is the capabilities of modern technology to which are due great credit for though the above-mentioned persons have become both contributors and friends, I have not ever met any of them!

The one to whom I owe the most is my wife, Dorothy, who gave me the support I needed to complete the long journey of experiences, learning, and writing which produced this book. Thank you Dorothy. Know you're needed, loved, and cherished.

Disclaimer

This book is replete with specific and general recommendations about the technology within. The author is a consultant; that is what consultants do – make recommendations. But one learns as a consultant to never make any recommendations to clients without knowing, from a first-hand evaluation, all their local circumstances.

That's why all the recommendations made in this book (about solvent selection or replacement, hazard management, material selection, management approaches, regulatory compliance, purchasing methods, etc.) are made without any knowledge of local circumstances and certainly without first-hand evaluation.

ALL recommendations made in this book are based on the technology being described, and should in no case be adopted without evaluation of the local circumstances.

What You Can Do with This Book

This is a book about the chemistry and engineering of cleaning surfaces with solvents. It is a book based on the science of chemistry, the disciplines of engineering, and the experiences of this author and his associates.

If the guidance found in this book is followed to a moderate degree, the user will have the information and basis to:

- *Make good decisions* about selection of solvents and facilities to be both effective in dissolving soils from surfaces, and protecting the personnel who use them as well as the environment into which they are used, and to
- *Have knowledge necessary to implement those decisions.*

This is not a book about "green chemistry". It doesn't recognize "green solvents" as such. The author doesn't believe in either concept. Solvents are solvents. They don't have a color (although, actually, a few do...).

All solvents can be used in facilities designed to contain them, protect the persons who use them, and the environment in which they are used. Proof of this is the normal use today in Germany and other European countries of methylene chloride, trichloroethylene, and perchloroethylene in totally contained facilities. Emissions are nearly zero. Contact by users with solvent is negligible.

Every solvent imposes a risk to those who use it and the environment in which it is used, can yield a benefit for using it, and requires a sound experienced-based plan to manage that risk. The purpose of this book is to describe the solvent including its benefits and risks, and explain the plan for management of that risk. The choice about use of any solvent is up to the reader.

This book (and its author) expresses no preference for any type of cleaning technology – aqueous, plasma, blast impact, no-clean, or solvent. It is not a paean to or a sonnet about the 'wonders' of cleaning surfaces with solvents, a craft well and long-used, if less so in recent years.

This book is based on a set of beliefs that there is no single or best way to successfully complete a surface cleaning task, that every method considered will present to the user a choice among benefits and risks, and that information exists which illuminate both.

The choice of cleaning method depends upon the details, and values – of the application, and of the staff administering it.

The aim of this book is to present adequate information for that staff to choose and implement whatever choice of method they prefer for each application.

This book will guide anyone who knows something of solvent chemistry and process equipment to successfully initiate and operate a system for cleaning surfaces of articles with chemical solvents.

The initial step in this work is to make the right selection of cleaning solvent. No choice is more important. The wrong choice of solvent will increase the risk of legitimate safety, health, and environmental (SHE) concerns. Chapters 1, 2, and 4 show that because solvent structure determines solvent properties, the science of solubility parameters is the most reliable basis for solvent selection. Solvents matched to soils have the best chance of providing optimal surface cleaning. Chapter 4 and Appendix D1 show how to reduce SHE concerns in an existing cleaning system by substituting one solvent raising less concern for another raising more concern, yet still maintain effective cleaning performance.

A secondary and no less essential step is to manage the chosen cleaning solvent so as to neutralize any toxicological threat it poses to humans. Chapter 5 shows that valid scientific information about SHE hazards is the key to neutralizing hazards, and provides guidance about how to identify that information and use it to contain those threats.

The emission of essentially all solvents produces atmospheric smog. This awareness leads to users to seek protection from increasingly more stringent legal regulations which limit use and emission of solvents so as to prevent formation of smog. The chemical basis for smog formation is described in Chapter 6. Also included is a detailed discussion of how and why some solvents are exempt from these regulations. Subchapters 6.8 and 6.9 describe how to manage solvent selection to reduce the potential for smog formation by emitted solvent fumes. Appendices B1 and B2 supplement this trove of information. The former provides more detailed information for the interested user about atmospheric chemistry. The latter explains how to predict which solvents will generate less smog.

An issue which must be under control, but is seldom covered in a balanced manner, is the economics of using solvents to clean parts. Chapter 7 provides information which is normally confidential – comparative prices of solvents in commerce at the same time. But it is also shown that the main cost element of parts cleaning is not keeping the tank filled with solvent. Rather it is the cost of compliance with environmental regulations concerning the disposal of spent cleaning solvent (containing soil) from cleaning machines. Successful strategies, tactics, and equipment for managing the cost of solvent cleaning are disclosed.

Cleaning work with solvents is also done outside of machines. Critical work is done with fabric wipers and selected solvents; less critical work is done by spraying commercial solvents on soiled surfaces from aerosol cans. Chapters 9 and 10, respectively, describe the advantages, methods, and hazards of implementing both non-machine methods of solvent cleaning. One can economically formulate their own wipe cleaning solvents from the information contained in Chapter 9. Appendix A4 is a compendium about compatibility of solvents with surfaces: metal, plastic, elastomeric, and human.

Not a mystery, nor to be ignored, is the science of solvent stabilization. One can't use some halogenated solvents, especially n-propyl bromide, without management of stabilizer additives. Chapter 11 simplifies this science, which is not based on what's often expected, and describes how and why some commercial stabilizer packages are formulated. As with wipe cleaning solvents, it is perfectly possible to purchase fine chemicals and save money or improve solvent life by formulating one's own stabilizer packages.

Publications covering industrial cleaning technology often include Question-and-Answer (Q&A) sections that are limited in background information, explanation, and details. Chapter 12 of this book is not so limited. Twenty one questions, or situations, are proposed and discussed. Aqueous cleaning is compared to solvent cleaning; both are compared to blast cleaning. The rationale for management of the market for cleaning solvents and the pricing of cleaning solvents are disclosed. Composition and cleaning potential of various commercial solvent blends are listed and recommended. In addition, two unusual and unrelated topics are covered: the use of odor to manage solvent exposure and the future of the solvent cleaning industry.

But there is more here as well. Some users, and manufacturers of equipment, want to calculate the properties of solvent blends. In general, blend rules for each physical or chemical property are different. Appendix A3 is the library of blend rules. A consistent nomenclature is used to calculate blend properties such as density and viscosity, solubility parameters, heats of vaporization, surface tension and exposure limits which require complex and unexpected approaches, activity coefficients, composite vapor pressure, flash point and lower explosion limits, and relative evaporation rate. To support these tabulations and derivations, working examples for each property are provided. The rules are supported by scientific references.

Finally, one can compare solvents using data (physical, chemical, flammability, environmental, regulatory, solubility) for 210 cleaning solvents in Appendix A1.

A Note on Organization

The content of this book is arranged in three layers. The top layer is a story illustrated in color. As a writer about technology and its use, I strive to communicate as a storyteller.

The story is always about the technology: the reasons for its use, or methods by which it was created, the science underlying it, the engineering by which it is applied, and the expected outcomes produced by it. A good story in this book has a beginning (that's the reasons and methods), a middle (that's the science and engineering), and an end (that's the outcomes). A successful teller of stories uses colored images to explain, and perhaps augment. Most of the chapters in this book were prepared by first developing the story through technical research, then planning the sequence of images which would tell the story without text, and finally writing the text. *One may read the main text (the story) and understand all that was intended.*

The second layer is within the footnotes (and boxes), and is found on the page of the citation. This material contains information not essential to the story, but of interest to some readers. The second layer contains internet references for sources which are thought to be useful. These may be reliable monographs published by suppliers, reports published by government agencies, websites maintained by academic sources who provide either additional or background information or relevant opinions, the technical basis for cited calculations, a chronology of events, restatement in different language of points made in the story, background about persons who contributed to the development of the chemical or physical technology used in solvent cleaning, or recognition of sources for images not prepared by this author. Of course, the problem with citation of internet references is that their existence and URL identification, while current as of publication is not necessarily permanent.

The third layer is within the endnotes found at the end of each chapter. These are conventional literature references, such as citations of journal articles or books. The most complete citation available is provided; if page or volume or issue numbers aren't given, it's because they couldn't be found.

This book is a collection of interrelated, intact, and intensely cross-referenced chapters. Together they tell a story about use of solvents in cleaning operations. But they do not comprise a story where each chapter must be read in sequence to understand it. One can start their understanding of the story anywhere in this book.

The content of this book also includes a considerable variety and amount of supporting material – twenty-one appendices. The contain basic data about cleaning solvents and their use, the reaction chemistry of ozone formation from VOCs, methods by which solubility parameters can be both measured and calculated, and the results of new research conducted by the author. Each appendix is written in the same three-layer manner as above.

Finally, this book is written for modern readers who are accustomed to reading materials formatted with the hypertext protocol. This allows readers use links to 'jump' to supporting references, explanations in other chapters, specific images or appendices, or definitions. Naturally, a book is a static structure and one can't "click on" a cited cross-reference. But one can turn pages.

Units Used in This Book

It would be easy to write that the units used in this book are those commonly used in the country in which this book was written (the United States), or to declare adherence to a specific system of units (English, SI, International, natural, etc.) because that system is believed to be the one most globally recognized or most frequently used or more based in science. But not all readers will be located in the US, nor will all have declared allegiance to one specific system of units. Today the span of any activity is both global in reach and compartmentalized by discipline. So it is not so easy to specify what system of units should be used in a book to be used in any country.

Instead, this book uses the units most commonly associated with the parameter being noted. Said another way, *the units used in this book are those recognized and used by readers actually doing solvent cleaning*. Those persons may be familiar with or educated in chemistry or physics; chemical, mechanical, or environmental engineering; industrial hygiene, industrial safety, or something else. In other words, those practicing solvent cleaning will have many and various preferred systems of units. Consequently, the system of units used in this book is mixed: The flammability classifications of the globally-recognized National Fire Protection Association (NFPA), for example, are temperatures scaled in degrees Fahrenheit – although they could be based on scales of degrees Celsius (Centigrade), Rankine, or Kelvin. So where flammability classifications based on temperature are given in this book they will be denominated in degrees Fahrenheit (°F). But the default unit used in this book for scaling of temperature is degrees Centigrade (°C). For convenience, a temperature may be noted in both scales, °C and °F.

Similarly, the unit most commonly associated with a solubility parameter is the square root of a pressure denominated in megapascals, or $MPa^{½}$[1,2]. But the default unit used in this book for scaling of positive pressure is the pound force per square inch (psi) because the pressure vessels found in enclosed cleaning machines are denominated in that unit. Likewise, the default unit used in this book for scaling of negative pressure is the Torricelli of vacuum (torrV)[3] because the capacity of vacuum pumps used with some enclose machines are denominated in that unit. The unit most commonly associated by suppliers and users with surface tension of solvents is surface energy per area[4] denominated in dyne/cm[5], or dynes.

The default unit used in this book for scaling of energy is the BTU because refrigeration units used in vapor degreasers are denominated in that unit, and the default unit used in this book for scaling of

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[1] While often noted elsewhere as $mPa^{½}$ for other purposes, the nomenclature $MPa^{½}$ is most commonly used to denominate solubility parameters.

[2] Solubility parameters may also be scaled in units of square root of pressure scaled in calories per cc, or $(cal/cc)^{½}$. To get values of $MPa^{½}$, one multiplies values of $(cal/cc)^{½}$ by 2.0455. Pressure is also energy divided by volume.

[3] Often noted elsewhere as millimeters of Mercury or mm Hg, 1 torr is equivalent in pressure to 1 mm Hg. When levels of pressure are denominated by either mm Hg or torr, 0 values of each are ambient pressure (not absolute pressure). When levels of vacuum are denominated in mm Hg, the 0 value is total vacuum. When levels of vacuum are denominated in torr, the 0 value is ambient pressure. In other words, total vacuum may be expressed as 760 torrV or 0 mm Hg; ambient pressure may be expressed as 0 torrV or 760 mm Hg.

[4] An equivalent representation for surface tension is force per length.

[5] An equivalent unit for surface tension is the mN/m (milli-Newton per metre).

area is the square foot (SF), So the default unit used in this book for scaling of length is the foot. For convenience, smaller amounts of length may be noted in other scales, feet, inches, mils; meters, or cm; Angstroms or nm.

The unit most commonly associated with scaling of solvent density[6] is the gram per cubic centimeter (g/cc)[7]. But the default unit used in this book for scaling of mass is the pound (lb) at least because solvent prices are denominated in that unit. For convenience, often smaller amounts of mass will be noted in other scales, grams (g), or ounces (oz).

The default unit used in this book for scaling of volume is the cubic foot (CF) or gallon (gal) because size of vapor degreasers is denominated in that unit. For convenience, often smaller amounts of volume will be noted in other scales, cubic centimeters (cc).

The unit most commonly associated by chemists with molecular weight is the gram mole. So the default unit used in this book for molar volume is the cubic centimeter per gram mole.

To summarize, units used in this book are chosen for recognition by those involved with solvent cleaning, not by those inhabiting a particular country, subscribing to a certain system, or educated in a specific discipline. The reason for this deliberate, if unorthodox, choice is to make this book more useful to those involved with cleaning of surfaces with solvents.

Units used in this book include the following:

Absolute temperature values	°K
Density	g/cc
Dipole moment	Debye
Energy	BTU
Flash point temperature values	°F
General temperature values	°C
Length	foot (ft)
Mass	pound (lb)
Molar volume	cc/g mole
Negative pressure	torrV
Positive pressure	pound force per square inch (psi)
Power	kW[8]
Refractive index[9]	dimensionless
Solubility parameter	$MPa^{½}$
Surface tension	dyne/cm
Universal gas constant	0.00788 BTU/g mole-°K (1.98588 cal/g mole-°K, or 8.31447 J/g mole-°K)
Volume	cc

6. Most ignore the fact that values of density denominated in g/cc are actually values of specific gravity: density stated relative to that of water.
7. Often noted elsewhere as kilograms per cubic metre.
8. Systems of units are further confused by the conventions about capitalization associated with the prefixes of units. The prefix mega (1,000,000) is noted as M, while the prefix kilo (1,000) is noted as k, the prefix milli (0.001) is noted as m, and the prefix nano (0.000000001) is noted as n. Even worse from the point of view of consistency, is the unit for power – noted above as KW (kilowattt). It is also noted in other sources as kW.
9. Measured at the yellow doublet sodium D line, with a wavelength of 589 nm, as is conventionally done.

Common Unit Conversions

1 BTU	= 0.25199 calories (cal)	= 1,055.05 Joules (J)	= 1.05505 kiloJoules (kJ)
1 cc	= 3.5315E−005 cubic feet (CF)		
1 dyne/cm	= 1 milliNewton/metre (mN/m)	= 0.001 kg/sec^2	= 6.852 × 10^{-5} lb force/ft
1 centipoise	= 0.001 Pascal-sec	= 0.001 kg/metre-sec	= 2.0885 × 10^{-5} lb force-sec/SF
1 g/cc	= 1000 kg/metre^3		
1 foot	= 30.48 cm		
1 lb	= 453.6 gram mass (g)		
1 inch	= 2.54 centimeter (cm)		
1 mil	= 0.001 inch	= 0.00254 cm	
1 KW	= 3,412 BTU/hr	= 238.84 cal/sec	
Temp, °C	= (1.8 x Temp) + 32 (°F)		

For those who prefer consistency of units, there is a simple, elegant, and free solution. One may-download and use the freeware program Master Converter, available from Savard Software (http://www.savardsoftware.com/masterconverter/). It is preconfigured to convert over 800 units in 42 categories, and can be configured to support any other unit in any other category.

External References Cited in This Book

This book is written to inform, to support ongoing or planned work with solvent cleaning systems, enable selection of the appropriate cleaning solvent, control safe and economical operations, and explain how desired results maybe obtained if they are not originally produced. One hopes it may also be enjoyed.

This book is not intended to stand alone as a reference or management tool for all cleaning operations. This book is about solvent cleaning. It refers to and is supported by information available in these other sources.

Other corollary references by this author support other aspects of surface cleaning:

Management of Industrial Cleaning Technology and Processes, published by Elsevier (ISBN: 978-0080448886), 2006. Coverage includes:

How all modern cleaning technologies work and should be used
US and global environmental regulations
Health and safety hazards associated with all cleaning agents
Control of industrial cleaning processes
Testing for cleanliness
Equipment used in cleaning, and their components
Statistical procedures for management of cleaning (or other) operations
Description of analytical procedures for cleanliness testing
Challenging situations in critical, precision, and industrial cleaning

In this volume, the *Management* book is cited as needed, to support discussions. It is always referred to as Ref. 1.

Cleaning with Solvents: Methods and Machinery (in preparation).

Coverage includes: *a detailed explanation of how vapor degreasers work including how parts are dried and solvent is contained, an analysis of how to specify and use an enclosed cleaning machine (vacuum or not), a discussion about cosolvent machines including the classification system for the various types, an illustrated explanation of recovery of solvent vapor from air by beds of adsorbent.*

Coverage also includes: *a detailed economic analysis of the operating cost of using all of the above solvent cleaning equipment.*

Handbook of Cleaning Solvents (in preparation). Coverage includes, for each type of solvent: its origin and synthesis, key applications where they or similar materials might be found as components of soil materials, analysis of any unique naming system, properties compared to those of other solvents, properties of specific solvents compared to those of others of the same type, significant hazards such as flammability and how and when to avoid them, significant environmental regulations which affect use, values of solubility parameters, comparison to specific soils for which use as a cleaning solvent is or is not recommended, and how their specific structure determines their specific properties.

Coverage also includes: general use of solvents and cleaning, how and why solvent structures are important, hydrocarbon solvents in general, aromatic and cyclic hydrocarbon solvents, industrial refined hydrocarbon solvents, soy-based solvents, terpene-based solvents (and stereochemistry 101), lactic acid based solvents, ionic liquids, oxygenated solvents in general, ether solvents, alcohol solvents, glycol solvents, glycol ether solvents, glycol ether ester solvents, ester solvents, ketone solvents, acid solvents, dibasic acid ester solvents, chlorinated solvents, brominated solvents, fluorinated solvents, nitrogen based solvents, silicon based solvents, specialty solvents, solvent azeotropes, and a database of binary azeotropes.

In the current volume, the *Handbook* is cited as documented to support discussions. It is always referred to as Ref. 3.

The author is also planning a series of digital documents which will include:

- Database of Binary Azeotropes
- Equipment for Vapor Degreasing
- Equipment for Enclosed Cleaning Machines
- Equipment for Cosolvent Machines
- Equipment for Treatment of Tailpipe Emissions

The Complete Naming System for Fluorinated Solvents

- Cleaning Test Results with Plant-Based Solvents

In this volume, these *Digital Documents* are cited as needed, to support discussions. They are always referred to as Ref. 4.