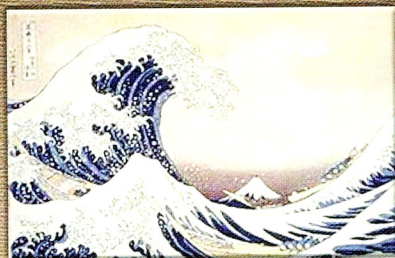


# THE ART OF THERMODYNAMICS

## PICTURES AT AN EXHIBITION



Valedictory Address

11 October 2002

Prof. dr. ir. Jakob de Swaan Arons

Handwritten notes in the top right corner of the left page, including the words "The Art of Thermodynamics" and "Pictures at an Exhibition".

The Art of Thermodynamics

Pictures at an Exhibition

Contents

On Art and Science

On Teachers

On Experiments

Some Poems

A Tradition

Process Efficiency

Sustainability

Acknowledgements

# The Art of Thermodynamics

## Pictures at an Exhibition

Valedictory Address

by

Prof. dr. ir. Jakob de Swaan Arons

Professor of Applied Thermodynamics and Phase Equilibria

Faculty of Applied Sciences

Delft University of Technology

11 October 2002

DUP Satellite / 2002

DUP Satellite is an imprint of

DELFT UNIVERSITY PRESS

P.O. Box 98

2600 MG Delft

The Netherlands

Telephone: + 31 15 2785678

Telefax: +31 15 2781661

E-mail: [info@Library.TUdelft.nl](mailto:info@Library.TUdelft.nl)

ISBN 90-407-2345-1

Copyright 2002 by J. de Swaan Arons

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without permission from the publisher: Delft University Press.

Printed in the Netherlands

Coverdesign by Sona Raeissi, Ph.D. student.

After "The Big Wave" from 36 views of the Fuji mountain by Katsushika Hokusai (1830)

## Contents

|                    |    |
|--------------------|----|
| On Art and Science | 1  |
| On Teachers        | 3  |
| On Applications    | 4  |
| Some Pictures      | 6  |
| A Transition       | 16 |
| Process Efficiency | 18 |
| Sustainability     | 20 |
| In Retrospect      | 23 |
| Acknowledgements   | 24 |

Contents

On Art and Science

On Teachers

On Applications

Some Pictures

A Transition

Process Efficiency

Sustainability

In Response

Abstracted Elements

DELFT Satellite is an imprint of  
DELFT UNIVERSITY PRESS  
P.O. Box 98 81  
2600 MG Delft  
The Netherlands  
Telephone +31 15 2785873  
Telefax +31 15 2781661  
E-mail: info@tupress.tudelft.nl

ISBN 90-407-3345-6

Copyright 2002 by F. de Swaan Arons

All rights reserved. No part of the material provided by this imprint may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without permission from the publisher Delft University Press.

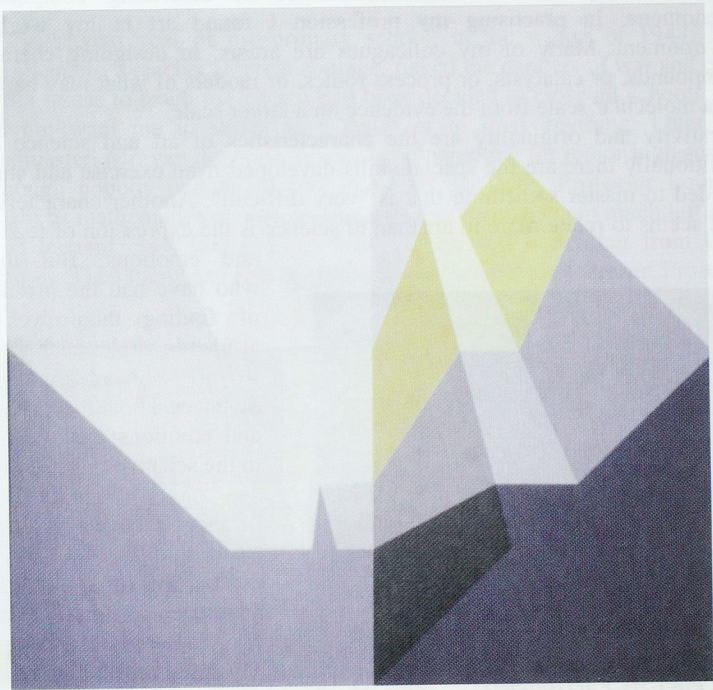
Printed in the Netherlands

Cover design by Sena Koceli, Ph.D. student  
After "The Big Wave" from 36 years of the Faculty of  
Engineering Helsinki (1870)

**On Art and Science**

My mother was a pianist, my father a violin player, and I consider myself a child of artists. But how different they were. My mother dedicated herself to technical perfection and interpretation. My father, to a certain extent, also subscribed to these ambitions but he found equal satisfaction in leading his colleagues with great enthusiasm. I must confess that I recognize some characteristic features of both of my parents in myself.

What about their three children? My youngest brother Robert is an artist, not only as a pianist, who has played for audiences, but also and even more



Picture 1. Variation 1. From "Série Cathare" (Robert de Swaan, 2002)

so as a painter, Picture 1. He is nicely settled in the southern part of France, as many painters have been before him. My other brother showed his early artistic skills in the classical sport of billiards in which he became a champion. Later as a mathematician, he designed an expert system for playing the beautiful but difficult game of three cushion billiards.

As my parents' oldest son, I was close to becoming a professional musician myself, but I searched for art in science instead and found it in thermodynamics. To be more specific, in applied thermodynamics. Thermodynamics is the ultimate science of the conversion of energy and matter, and its power and beauty become apparent in its applications. It is rich in elegant scientific formulas of variable complexity, often enriched in appearance by Greek characters, Picture 2, describing complicated phenomena. In practising my profession I found art in my working environment. Many of my colleagues are artists: in designing chemical compounds, or catalysts, or process routes, or models of what may happen on a molecular scale from the evidence on a larger scale.

Creativity and originality are the characteristics of art and science and additionally there are the special skills developed from exercise and study, needed to master something that is "very difficult". Another characteristic that seems to relate more to art than to science is the expression of feelings and emotions. But those who have had the privilege of finding themselves in academic circles such as our Royal Academy of Sciences, know that feelings and emotions are not alien to the scientist.

$$E_{1in2} \cong \frac{1}{\varphi_{1in2}^{\infty}}$$

$$\ln \varphi_{1in2}^{\infty} \cong 2B_{12}\rho_2^0$$

Picture 2. Estimation of the enhancement in solubility of a solute 1 in a supercritical solvent 2

In short, I have always felt attracted to the artistic component of science and have tried to be an artist in applying thermodynamics. My appointment to the Delft Chair of Applied Thermodynamics and Phase

Equilibria gave me an excellent opportunity to do this. But just as a painter does not want to be measured by the number of square metres he has painted, as my respected colleague Jan Verhoeven used to say, I hope that I will not be measured by the volume of my output.

## On Teachers

It is the privilege of a professor to teach. Since my appointment in Delft I taught thousands of students. But once I was also a student myself and some of my teachers made a permanent impression on me. I have never forgotten them and will always be grateful to them.

In the second year of my primary school, in the winter of 1944, Mrs. Glaudemans, a teacher of great courage, risked the dangers of war and came to our house to teach me after it had been decided to close all schools. She did not want me to suffer as a result or to miss anything. Later, my headmaster, Mr. van der Gast, privately prepared me for junior high school, although nobody had asked him to do so. In Delft, Professor Loonstra taught us mathematics in such a clear way that there was not much left to be done beyond class hours. Even today, I am still benefiting from those lectures. Then there was also my beloved teacher and predecessor, Professor

Joris Diepen, Picture 3, who introduced us to chemical thermodynamics and phase equilibria. My admiration for him was so great that it never crossed my mind that I might one day succeed him. That was until he asked me. His lectures were unforgettable and of the same beauty as his interpretation of some of the sonatas by Beethoven. At his 85<sup>th</sup> birthday celebrations, instead of giving a formal



Picture 3. George "Joris" Diepen (1910 – 1995). My beloved and gifted teacher

speech, he played one of these sonatas to thank us for attending. He died a few months later.

One does not need to have attended classes to consider somebody one's teacher. Books and scientific articles help to identify one's distant teachers. For me these teachers were John Prausnitz in molecular thermodynamics, Terrell Hill in statistical thermodynamics, Ilya Prigogine in irreversible thermodynamics and Albert Lehninger in bioenergetics and biochemistry. I am most grateful to all of them.

Our University has an illustrious institute, the Delft University Foundation, "that reaches the parts others don't". One of its board members, Peter Rauwerda, had the wonderful idea of honouring Delft's distinguished teachers with the Leermesterprijs. Awarding this prize is one of the annual highlights of our University and some of my respected and close colleagues Arnold Verruyt, Jurjen Battjes, Herman van Bekkum, Ted Young and Jacob Fokkema, were the happy recipients of it and rightly so.

## On Applications

While I was a student, Delft gave me an excellent scientific foundation. But during a one-year spell as a research assistant in Yale University's Chemical Engineering Department, I discovered the great distance between science and engineering. I was referred to the famous book on thermodynamics by Lewis and Randall. The chapters on entropy and fugacity are pieces of sheer art and essential for learning how to apply thermodynamics in practise.

What the true applications of thermodynamics are, I learned with my first employer Shell International, at Shell Development in Berkeley, California, and at the Shell Laboratories in Amsterdam. Oil, natural gas and petrochemicals became my territory with most products in the fluid state. I felt most comfortable when these fluids were neither liquids nor gases but prevailed in the near-critical state. After all, I was a student of the Delft School where my predecessors Diepen and Scheffer had gained well-deserved recognition with their insights in supercritical fluids. I learned to bring theory into practice, to produce numbers, have the courage to release them and feel responsible for them.

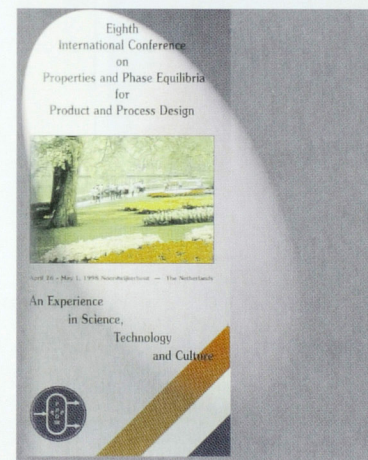
It also put me in an excellent position for my later tasks in Delft. In those first years in the early 1980s, government money for university research could only be acquired if this research had the prospect of being "relevant for society". My associates and I had quickly formulated a programme in which we could do the research we wanted to do, at the same time assuring its "relevance for society".

Gradually we attracted important industrial sponsors, Shell, Gasunie, AKZO and DSM to start with, who ensured that our group would be in a comfortable financial position. We will never forget this and will always be grateful to them. Not much later the Netherlands Science Foundation gave us a significant financial injection to extend our experimental facilities. We were able to take off along a very productive and prosperous road that led us to a frontier position in the international professional field. The icing on the cake came many years later when we were assigned the organization of the top meeting in our field, Picture 4, with state-of-the-art lectures, a reception in the Mauritshuis, a dinner in Huis ter Duin, the Keukenhof exhibition and the first John M. Prausnitz Award. They are all unforgettable events when strong professional ties were established.

events when strong professional ties were established.

In the meantime the First Lady of Thermodynamics and earliest friend of the Delft Laboratory, Anneke Levelt, received an honorary doctorate from Delft University on the occasion of its 150<sup>th</sup> birthday. So did her husband, Jan Sengers. A unique event. Jan thanked the University for this distinction because it allowed him to witness the honourable graduation of his wife from nearby. As her honorary promotor I should thank Anneke because through her I had the opportunity to meet Queen Beatrix!

Some of our work in those years will now be briefly discussed.



Picture 4. *The 1998 International Conference in Noordwijkerhout. A highlight in the recent history of the Delft Laboratory*

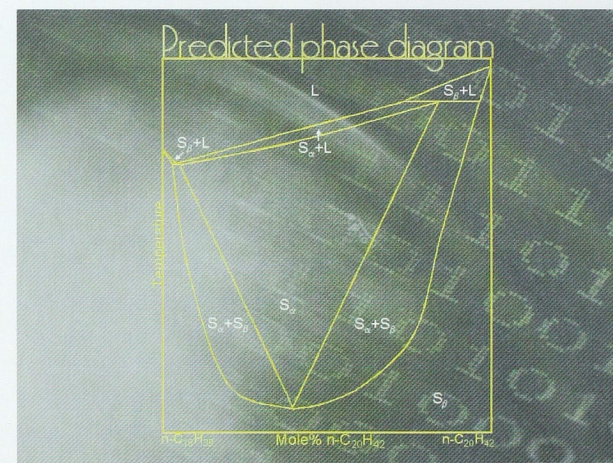
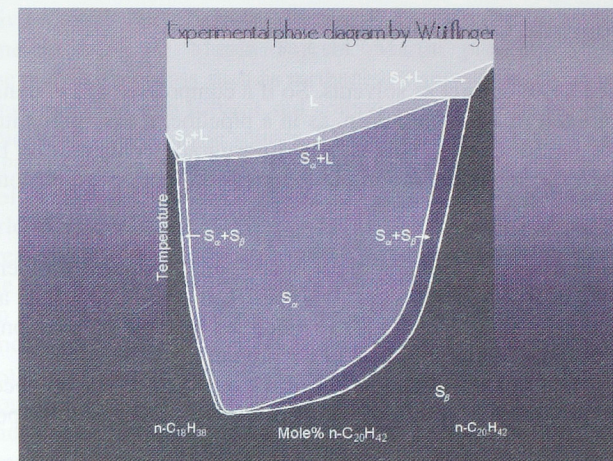
## Some Pictures

### The Girl from Zeeland

One day on one of my regular visits to Professor Gerhard Schneider, a world-famous expert in phase equilibria, in Bochum, he introduced me to Professor Würflinger, one of his associates. The latter had made accurate studies of solid and liquid paraffin mixtures at high pressures and gave me his thesis. A picture can tell more than a thousand words and from the phase diagrams in his thesis I quickly understood the phase behaviour. Not much later Unilever's Solke Bruin, an old friend from Shell, asked my opinion about their work on the phase diagrams of fats in margarines. Could this work possibly form the basis of a Ph.D. thesis for one of their talented young researchers, Leendert Wesdorp? Less than two years later Leendert had developed an impressive thermodynamic model for mixtures of solid and liquid fats, based on the insight that we had obtained from Würflinger's work, Picture 6a. Würflinger's diagrams could be qualitatively reproduced from setting some parameters in the model at realistic values, Picture 6b. We understand that this thermodynamic model has provided a useful basis for the manufacturing of margarines and even become part of a business model. Leendert is now one of Unilever's research directors.



Picture 5. *Zeeuws Meisje*. A famous brand in margarine



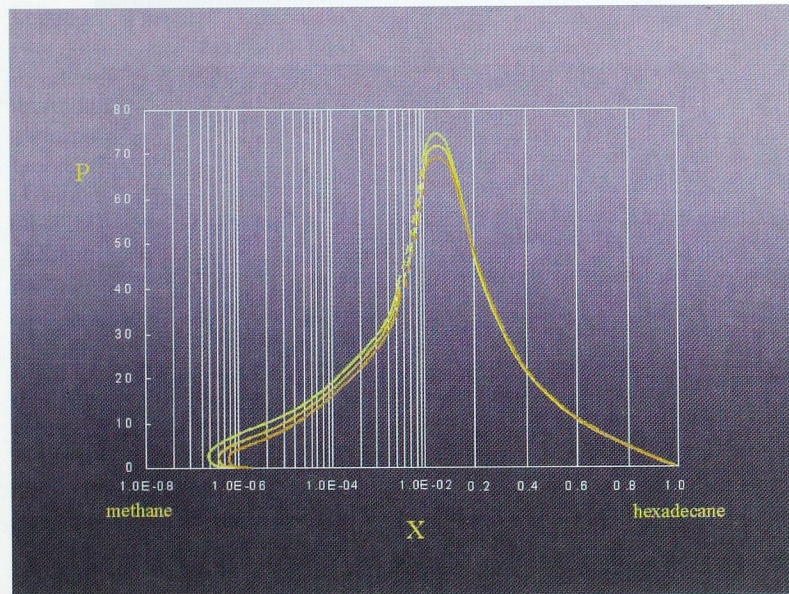
Picture 6. a. Würflinger's data on paraffins inspired the development of the "margarine" model  
b. The model was later applied to his original data.

## Retrograde Condensation

Compressed gases can act as solvents. So if a compressed gas is transported and is submitted to a pressure drop, as in a pipeline, it may precipitate tiny amounts of liquid solutes. This is called retrograde condensation because usually one expects condensation on compression, not on expansion of the gas.

While distributing gas, Gasunie experienced some technical problems as a consequence of this phenomenon. At Shell I had heard about this, and had even developed a simple model for it which led to some publications, but I had never become further involved in the problem.

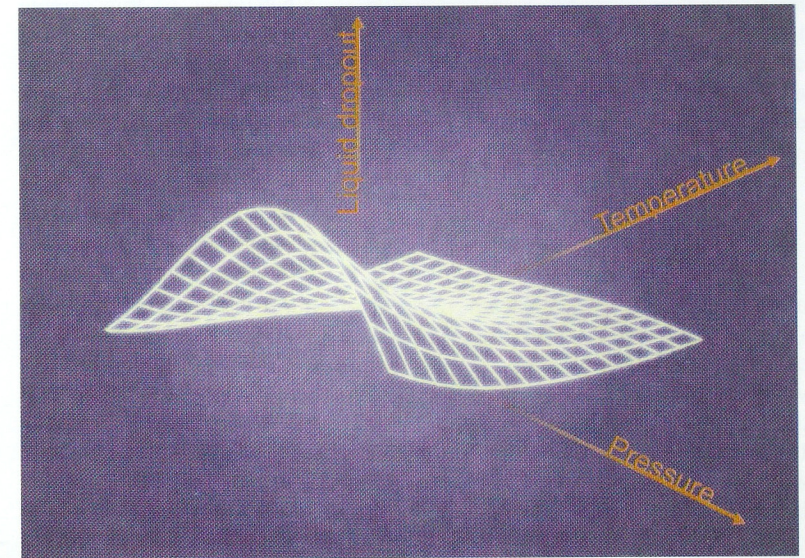
After my arrival in Delft, Gasunie asked for our help. It was to become an eight-year programme resulting in two Ph.D. theses and a powerful



Picture 7. Retrograde Condensation. Some of Rijkers' beautiful data on the solubility of n-hexadecane in supercritical methane

predictive model for Gasunie. Picture 7. shows an example of the experimental work of Marijn Rijkers. Marijn produced a wonderful database with components such as methane, ethane and nitrogen to simulate the compressed gas as a solvent and components like benzene, hexadecane etc. as the dilute low volatile solutes. The next phase was taken care of by a Greek Ph.D. student, Marianna Voulgaris, scouted by us in Athens in the group of Professor Dimitrios Tassios. Scouting is not only the privilege of the world of soccer.

As a great talent in thermodynamic modeling and basing herself on Marijn's accurate database, she predicted the amount of liquid dropout, Picture 8. For a given natural gas consisting of hundreds, perhaps even thousands of components, she could predict the amount of separated liquid as a function of pressure and temperature. We persuaded Gasunie to undertake field tests to test our predictions. They did so at vast expense, but did not regret it. The predictions were excellent and gave Gasunie an edge in negotiations with customers.



Picture 8. Retrograde Condensation. Principle of Voulgaris' powerful predictive model

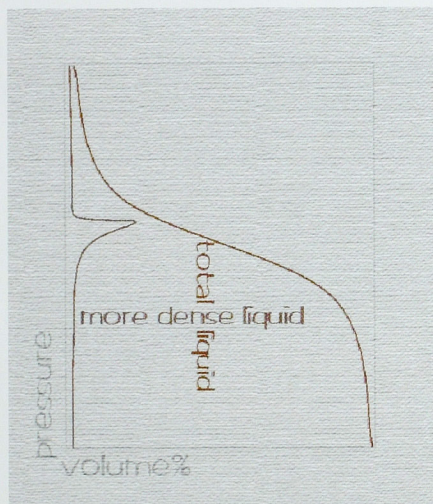
Some years later our insights turned out to be very useful when we assisted a multinational client in an important court case. It was to their advantage. Good research pays, but rarely right away.

These experiences were also an illustration of the synergy that is possible when working closely together, as my associate Cor Peters and I have done for many years.

### On Theory and Experiment

This was the theme of the late Professor Donald Robinson's keynote lecture at an international conference, held in Banff in 1989. Don reported on a high pressure gas condensate sample from Newfoundland. His calculations

with the well-known Peng-Robinson equation of state on the phase behaviour of this sample did not correspond at all with what he experimentally found in his laboratory. What he measured was not at all usual, Picture 9. On reducing pressure, a liquid separated. While this liquid, the so-called retrograde condensate, was still accumulating, a second liquid formed, built up to a maximum amount and then disappeared. Nobody could explain this remarkable phenomenon and the Peng-Robinson equation of state did not predict it.



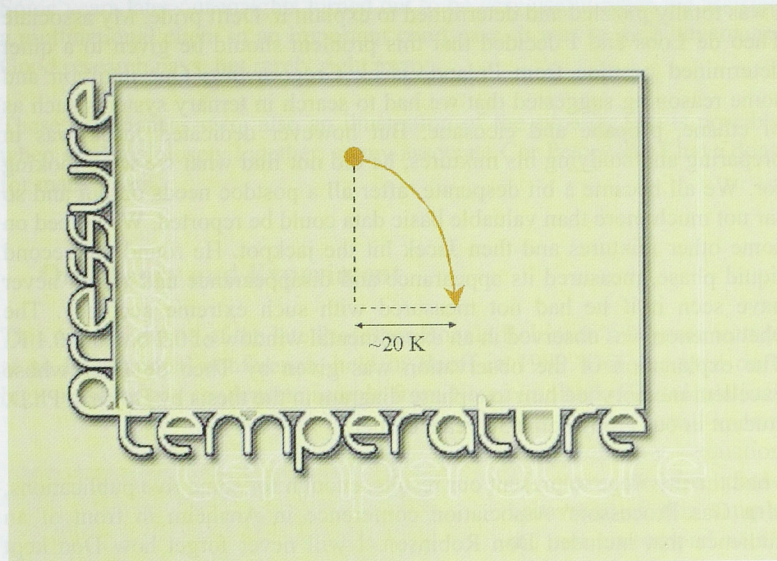
Picture 9. Robinson's puzzling observation that during retrograde condensation a second liquid appears and disappears

I was totally puzzled and determined to explain it. Delft pride. My associate Theo de Loos and I decided that this problem should be given to a quiet determined postdoc from Poland, Jacek Gregorowicz. Our intuition and some reasoning suggested that we had to search in ternary systems such as of ethane, propane and eicosane. But however dedicated Jacek was in preparing and studying his mixtures, he did not find what we were looking for. We all became a bit desperate, after all a postdoc needs output and so far not much more than valuable basic data could be reported. We agreed on some other mixtures and then Jacek hit the jackpot. He found the second liquid phase, measured its appearance and disappearance and would never have seen it if he had not measured with such extreme accuracy. The phenomenon was observed in an experimental window of 0.2 bar and 0.1 K. The explanation of the observation was given by Theo de Loos whose excellent memory led him to a phase diagram in the thesis by Bayle, a Ph.D. student in our group some 30 years earlier.

I had the privilege to present our results, enough for some five publications, at a Gas Processors' Association conference in Anaheim in front of an audience that included Don Robinson. I will never forget how Don kept shaking his head in disbelief, later complimenting us on this effort. By the way, we could also show that his own Peng-Robinson equation of state is perfectly able to take account of such phenomena, provided that the problem is properly formulated.

### From Lecture to Application

One day I attended a lecture for graduate mechanical engineering students given by my associate Hedzer van der Kooi. The subject was the Joule-Thomson coefficient  $\mu$  and its sign in the PT plane. We are familiar with the fact that a gas cools on adiabatic expansion, although I happened to know that gases like helium and hydrogen could also heat up on expansion, provided the conditions are right. Hedzer's analysis with an equation of state gave a more complete picture and showed that at high pressures this phenomenon is quite common. I had never seen it before and it intrigued me.



Picture 10. Oil and gas reservoir fluids may heat up upon expansion

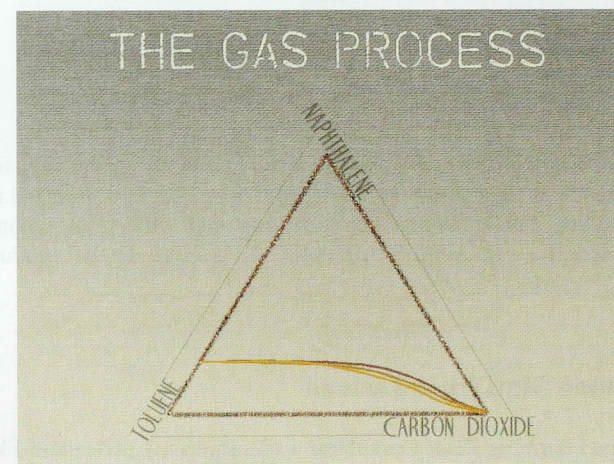
Somewhat later I attended another meeting of the Gas Processors' Association in the United States. In a parallel meeting on basic data needed for the natural gas industry, a colleague, working for a multinational oil industry, urged that more attention be paid to the Joule Thomson coefficient. After the session I asked him where his interest for this property came from. Then he told me that very high pressure oil and gas fields "out there" (referring to the North Sea) appeared to heat up on production rather than cool down, causing some unexpected problems.

On my return to Delft I asked a Ph.D. student, Diomides Stamoulis, to explore methane's Joule-Thomson coefficient. He gave the first evidence for this anomalous behaviour but it took a very intelligent and effective graduate student, Walter Kortekaas, to draw the full picture of natural gas fluids, so-called gas condensates, with a high content of high molecular weight compounds. Indeed, adiabatic expansion of such fluids can result in a temperature increase rather than a decrease, Picture 10. Such studies are of

great importance for the development and production of high pressure gas condensate reservoirs.

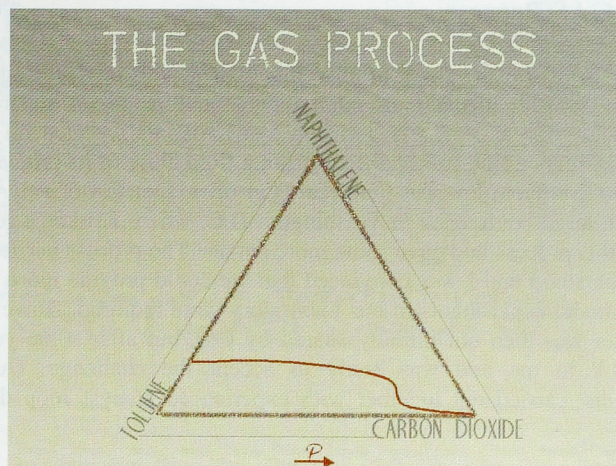
## The GAS Process

Scientists have the privilege of travelling extensively and seeing many places. In 1988 I attended an international conference on supercritical processes in Nice and on this occasion Val Krukonis reported on a new process to produce fine solid particles from a fluid close to its critical state, the Gas Anti-Solvent Process. One year later my associate Cor Peters and I attended a large conference in Washington D.C. where Krukonis reported again on this process and gave some more details. The process needed to be better understood and I was convinced that we could provide more insight and that model experiments in our Laboratory were required. However my enthusiasm was then not initially shared by Cor, but after some years he came back to me and was ready to accept the challenge. Our first experiments, carried out together with experienced analyst Joop de Roo,



Picture 11. The Gas Anti Solvent (GAS) process. The supercritical solvent can act as co-solvent and anti-solvent.

were a failure, with crystals dissolving rather than precipitating. With a very talented postdoc from Chile, Juan C. de la Fuente Badilla, we unravelled the mystery of the process and discovered that the same near-critical solvent



Picture 12. The GAS-process. Crystallization controlled by subtle changes in pressure

could act as a co-solvent and an anti-solvent. Our model system consisted of carbon dioxide as the co-/anti-solvent, naphthalene as the solute and toluene as the solvent. The transition can be fine-tuned with subtle changes in pressure and the fine solid particles of the solute can be produced or dissolved, Pictures 11. and 12.

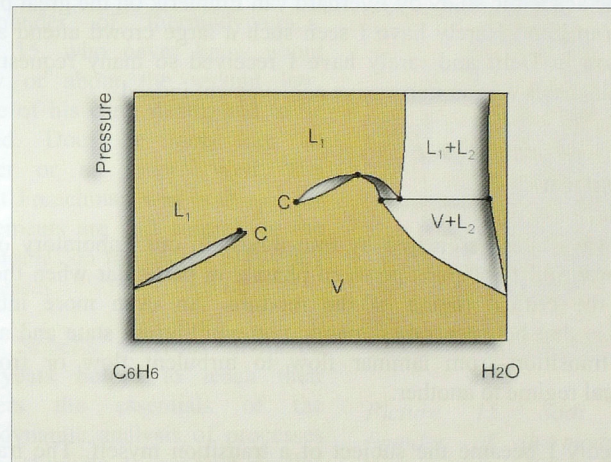
### A Young Man from Zeeland

Modest and charming Peter Cornelisse walked into my office and I knew it right away. This young man was not only very smart but was probably smarter than I was. Someone like him requires special attention and

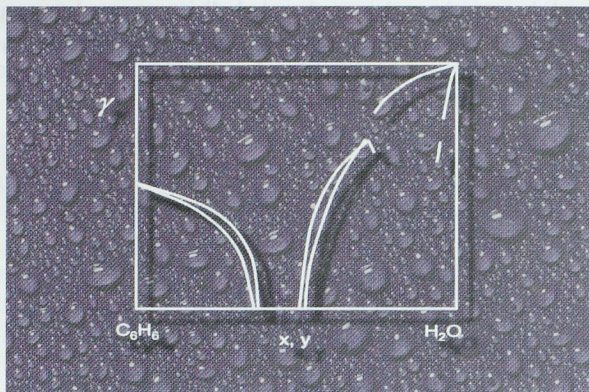
coaching. A beautiful pearl in a closed shell is entrusted to you. The only thing you have to do is to let it open up properly and nurture it, that is all. Peter's Ph.D. thesis, just like the thesis by Leendert Wesdorp, was awarded with "cum laude", a rare achievement in Delft.

Peter showed an extraordinary control of mathematics, superior in this respect to his supervisors' and this enabled him to apply Van der Waals' gradient theory to the simultaneous prediction of phase equilibria and interfacial tensions of mixtures. This possibility had been suggested by Cor Peters, his direct supervisor, during one of his lectures in an advanced course. Pictures 13 and 14 show results for the complex phase behaviour of mixtures of water and benzene and the corresponding behaviour of the interfacial tensions.

Peter was also able to predict from his studies when phases would start selectively wetting or covering each other and how a third component in a ternary system could act as surface active agent by increased concentrations at the interface, sometimes preceding the emergence of a new phase. Peter is now a successful consultant in a multinational oil company.



Picture 13. Prediction of complex phase behaviour in mixtures of water and benzene



Picture 14. Simultaneous prediction of interfacial tensions of mixtures of water and benzene

Before passing on to the next section I should not forget to mention a remarkable academic study by Everhard van Emmerik on the great physical chemist Van Laar. Rarely have I seen such a large crowd attend a Ph.D. examination in Delft and rarely have I received so many requests for a thesis! This thesis was an impressive achievement indeed.

## A Transition

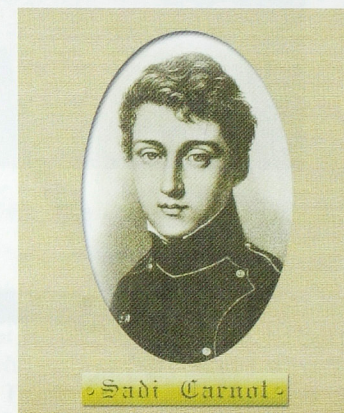
I have always been fascinated by transitions. In our Laboratory one can observe beautiful transitions between phases, in particular when they take place in the critical region of the mixture. An even more intriguing transition is that between one dynamic non-equilibrium state and another, like the transition from laminar flow to turbulent flow or from one biochemical regime to another.

Unexpectedly I became the subject of a transition myself. The transition was one from phase equilibria, equations of state and mixing rules - an area which I had intensively covered with my nearest associates as the traditional

area of our Laboratory - to the efficiency and sustainability of processes. There may have been some factors responsible for this. During my five years with Shell Coal in London I made an extensive thermodynamic study of power stations. After my arrival in Delft Professor Jan van Lier invited me to the mechanical engineering faculty to add to their curriculum what, in his opinion, was missing: the thermodynamics of phase equilibria at high pressure. Professor Esso de Jong of the same faculty asked me to take the initiative in an industrial multidisciplinary project on supercritical solvents, a project as promising fifteen years ago as it is today. Most influential was Jan de Graauw, Professor in Process and Equipment Design, who was a great supporter of using thermodynamics in process design. One way or another, these three colleagues of a neighbouring faculty tempted me to enter another world.

I discovered that I wanted to understand the world of process design, of process routes. Energy consumption appeared to be the clue and unexpectedly I could fall back on another famous teacher who I had studied in my spare time many years before:

Ilya Prigogine on the thermodynamics of irreversible processes. Sadi Carnot, the founder of thermodynamics, Picture 15, who never knew about entropy or about the second law, because of his early death, had to be revisited. Does he look like an engineer or an artist? Well, this brilliant Frenchman was both and his achievements are still controlling the many studies on the energy efficiency of processes.



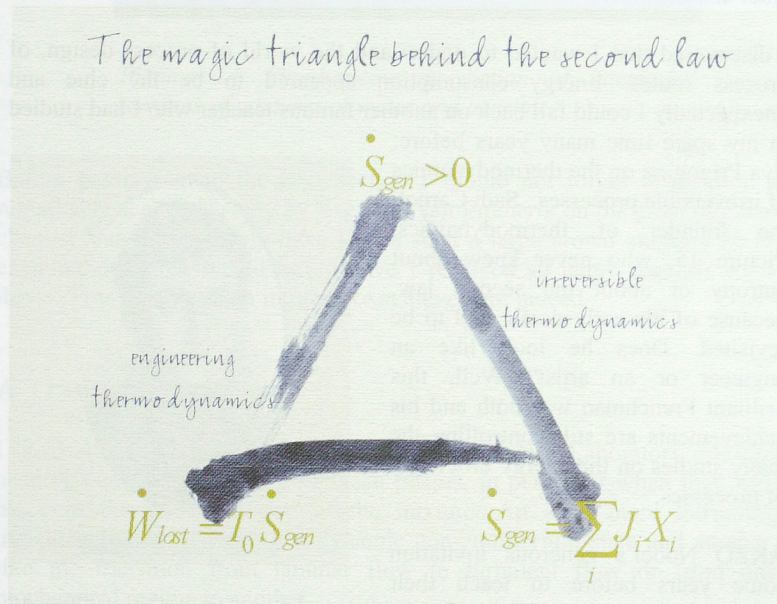
AKZO Nobel's generous invitation some years before to teach their engineers the essentials of the thermodynamic analysis of processes was a stimulus to proceed in this direction. For good teaching one needs a full understanding.

Picture 15. Sadi Carnot, founder of thermodynamics. Artist, engineer or both? Sadi refers to the artist's name of a famous Iranian poet.

All this greatly changed and enriched my professional life, and the subject of sustainability had not even entered it yet.

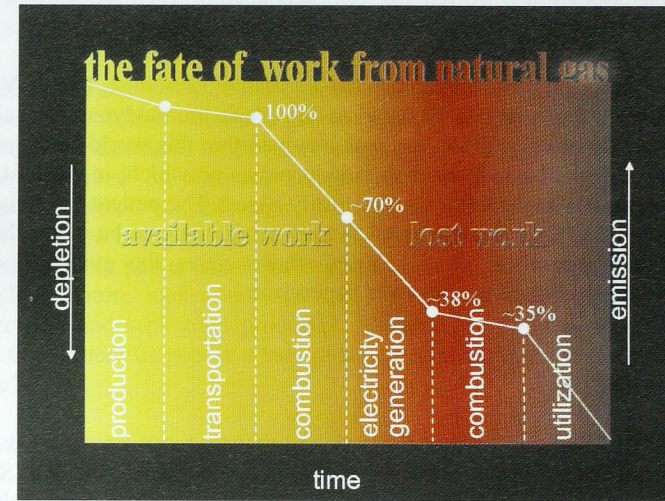
### Process Efficiency

On my new path I met Hedzer van der Kooi, the member of my staff who was most interested in processes, and our new alliance was sealed in a joint paper. From our studies with the many students we attracted by teaching this subject, we learned that if equilibrium thermodynamics tells us about matter and its equilibrium properties, non-equilibrium or irreversible



Picture 16. The Magic Triangle. The second law, irreversible and engineering thermodynamics interpret the limited efficiency of processes

thermodynamics teaches us about the process, its driving forces and the costs in terms of energy dissipation. We adopted the Magic Triangle that symbolized the essence of our work, Picture 16. We developed a two-coordinate system with the quality and quantity of energy as the coordinates and made a back-of-the-envelope analysis of complex processes as



Picture 17. The fate of work available in natural gas. Essential lessons sustainability

combined-cycle and co-generation processes to generate heat and electricity from natural gas, Picture 17. That is what Jan de Graauw wanted: he had so many ideas on process design but which one was the best and why. We could assist him in finding the answer. Thanks to Hedzer's initiatives our students moved on to many different industries to analyse their processes and establish the energy efficiency, sometimes with surprising results. Processes related to energy and chemical conversions as well as to separations. Peter Hinderink developed, under our supervision and that of Comprimo's Bas Kerkhoff, the first process simulator based on exergy calculations, EXERCOM. At the same time he made a thorough analysis of

the production of synthesis gas and came up with some innovative ideas. These studies formed the basis for a later study on the efficiency and sustainability of the chemical process industry.

A less pleasant observation that we made was that thermodynamics can be merciless in its analysis of processes. It is not always friendly to people with new ideas. Sometimes we felt like dull accountants when we showed that the money (read energy) simply was not there or had nearly dissipated.

It took a daring, tireless and somewhat frustrated economist, Sip de Vries, who I met through Jan de Graauw, to introduce thermodynamic analysis into the world of agriculture. Sip was annoyed that this world had ignored the lessons of the basic laws of thermodynamics on which, in contrast, the world of process technology was so firmly based. The patient teachings of Hedzer van der Kooi demonstrated that an economist can be persuaded to apply thermodynamics. Dr. de Vries' thesis gives the evidence, with Hedzer, Jan and myself as the proud supervisors.

## Sustainability

Unilever Research has always been an important sponsor of our work, not least because of the vision of my friend and old Shell colleague Solke Bruin, a former professor at Wageningen University. He was convinced of the significance of applied thermodynamics for Unilever's activities. Hans Broekhoff, a research director, invited us to make an extensive analysis of washing processes. Our former postdoc Xingmin Zhao then showed how traditional washing processes can be made at least four times more efficient in terms of energy. Further improvements would require drastic new process designs.

After this study Hans came back to us and was responsible for an exciting new component in our research and teaching. He raised a question that, as any good question does, contained half the answer. The question related to sustainability and its possible quantification. Sustainable development was a concept that had been catapulted into existence after the famous United Nations Brundtland Report in 1987. This question excited Hedzer and me to such an extent that we met at his house on the following Friday evening,

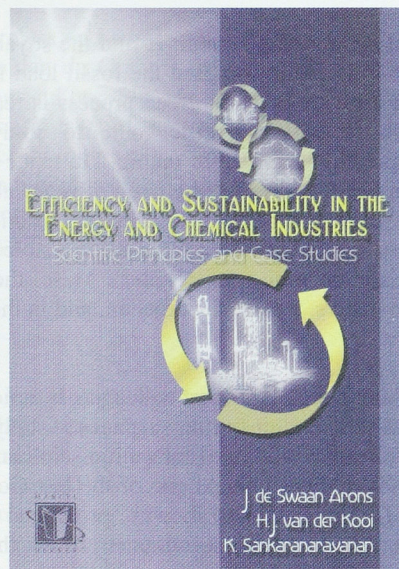
much to the irritation of his wife and mine, I must admit. That evening, and inspired by Albert Lehninger's beautiful monograph on bioenergetics, we developed an insight that was soon eagerly picked up by our students. Michiel van den Berg was the first student and perhaps the first ever to make a quantitative sustainability analysis, based on thermodynamic principles, of a process, namely the production of palm oil. Jan Maarten Mulder followed suit by comparing two different routes from solar energy to the same end product.

Marianne Schenk compared the hamburger and the soyaburger in terms of sustainability. Hans Wassenaar proposed the fossil load factor and showed how one can decide to what extent a green process is really green. Sander Lems embarked on a more scientific route to study what chemical engineering could possibly learn from nature. He made a thermodynamic analysis of the living cell, addressed the issue of renewability of resources and studied the power output of coupled chemical reactions, a mechanism of which nature makes extensive use in all possible types of energy conversion and separation processes. Sander's M.Sc. thesis resulted in at least three scientific papers, a rare phenomenon, and in the distinction "cum laude".

Ever since Joop Schoonman, my closest colleague, returned from Japan and gave me TRILEMMA, an inspiring Japanese study on sustainable development, I have realized the need for multidisciplinary efforts to attain certain goals of global dimensions. At one of the last Gordon Conferences on Frontiers of Thermodynamics I was privileged to meet Stefan Baumgärtner, a brilliant young economist from the University of Heidelberg who graduated in physics. Since then we have often communicated and we produced recently our first joint article on the thermodynamics of waste management. Economic systems have much in common with industrial systems. Stefan and I hope to demonstrate how thermodynamic principles should enter economic studies, in particular when they relate to ecological issues. Our well-known colleague Robert Ayres has already written an inspiring article on the topic of "eco-thermodynamics".

Professor Kazuo Kojima introduced me to The Cycle of Life and suggested writing a book on the many discussions we have had over the years on various occasions in China and Japan. "Efficiency and Sustainability in the

Energy and Chemical Industries" is the title of this forthcoming book. Hedzer van der Kooi and I are delighted to be producing the book, Picture 18, together with our former student Krishnan Sankaranarayanan who, we are pleased to report, has received his Ph.D. from Princeton University and has joined the Exxon-Mobil Corporation. A joint production by a student and his teachers, what could be nicer?



Picture 18. Cover design by Sona Raeissi of our forthcoming book. The joint production of a student and his teachers.

Worth mentioning is also the organization of the GRATAMA Workshop "Chemistry and Chemical Technology for a Sustainable Society" on the occasion of the commemoration of 400 years relations between the

Netherlands and Japan. In an unprecedented joint effort with my Japanese colleague Professor Tomoshige Nitta, and with the help of the Netherlands Science Foundation and the Netherlands Embassy in Tokyo, nearly 100 top scientists from both countries met in Osaka for four days. Addresses included those by our Crown Prince William of Orange, the Minister of Economic Affairs Annemarie Jorritsma, and the Presidents of Delft and Osaka universities Dr. Nico de Voogd and Dr. Tadamitsu Kishimoto. Six years of very close cooperation on a basis of friendship made this event memorable and a great success.

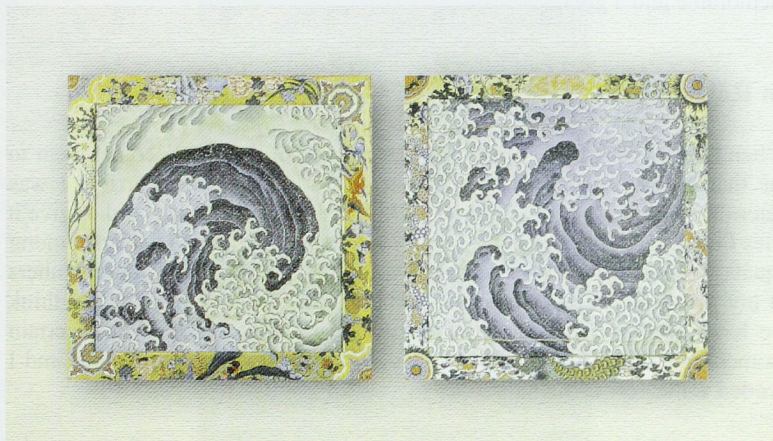
### In Retrospect

When I look back on the years that I have spent in Delft, it becomes clear to me that I was driven by a number of forces. Firstly, upon arrival I was determined to put the Delft Laboratory back on the world map and to give it a leading position in the international professional world. As the first among equals, I wanted to take responsibility and make sure that all the members of my group could fully develop their potential and give their best. I think we have been successful, but the price to be paid was that, at a certain moment, perhaps after 10 years or so, I felt more or less superfluous and I needed some new challenges.

The second driving force was curiosity, the drive to understand what seems puzzling, irrespective of whether society or industry has a need for a solution or not. A researcher should, to some extent, be like a bloodhound, with a good sense of smell, never letting go, continuously searching. The third force, perhaps somewhat specific to myself, was the pertinent will to apply what had become understood. A relationship with industry is therefore essential and is a two-way process as industry may often unconsciously define new research areas by formulating their problems.

The last and perhaps "noblest" driving force was the ambition to transfer knowledge by teaching, to present old and new insights, and to interpret the great masters of our profession. I did not flinch at showing a passion for the subject. It is my experience that a good lecture may be as equally overwhelming as a symphony, provided it has been well composed and conducted. This frequently stimulates the inquisitive and inspired student

who then questions the subject and wishes to discuss it further. Some years later this same student may wish to join your group and tackle a problem, accepting the conceptual design of a possible solution from his teachers and create new solutions and research ideas. This is the greatest reward for a teacher, as most of my colleagues will confirm, and sometimes a moving experience, Picture 19.



Picture 19. Female (left) and male versions of waves. Paintings by Hokusai's apprentice Kozan Takai based on his teacher's original sketches (1845; with the permission of the Hokusai Museum in Obuse, Japan)

### Acknowledgements

I owe a lot to my late parents. They survived the war but only just and had only one thing on their minds: providing a good education for their children. To reach that goal they sacrificed much, often forgetting about themselves.

I thank Shell Research for having prepared me so well for one of the most wonderful challenges one can imagine: to succeed one's teacher and become a Delft professor.

I thank Delft University for all the opportunities that they have given me. I am proud to say that in Delft everything is possible as long as you know what you want and they know you can do it. I thank the University also for the confidence they showed in me when assigning me to various responsible tasks.

I thank our sponsors DSM, AKZO Nobel, Shell, Gasunie and Unilever for their wonderful support.

I thank all the members of my Laboratory for their dedication, hard work and loyalty. I enjoyed a warm relationship with my closest fellow professors Joop Schoonman, Gert Frens and Herman van Bekkum. I felt very at ease with my colleagues in the Delft Chem Tech department and only wish I had been able to be closer to my colleagues in the Biotechnology department. I was particularly pleased with the design of Delft's first course on Thermodynamics for Biotechnology in cooperation with my respected colleague Sef Heijnen. The course was inspired by suggestions from John Prausnitz and was introduced at an international level with the help of the European Science Foundation.

I wish to express my great admiration for my German colleague and world citizen, Professor Emeritus Helmut Knapp who succeeded in a unique way in bringing European colleagues from industry and academics together. Eleven years ago, in Berlin, he asked me to consolidate this initiative and I am pleased to say that the European Seminars on Applied Thermodynamics are still alive and kicking.

I thank my colleagues in Beijing and Shanghai, and in Sendai, Tokyo, Osaka, Kyoto and Fukuoka for the many opportunities they have given me to teach, lecture or be active professionally in the Far East. My close friend and colleague Professor Wenchuan Wang deserves a special mention for his many initiatives.

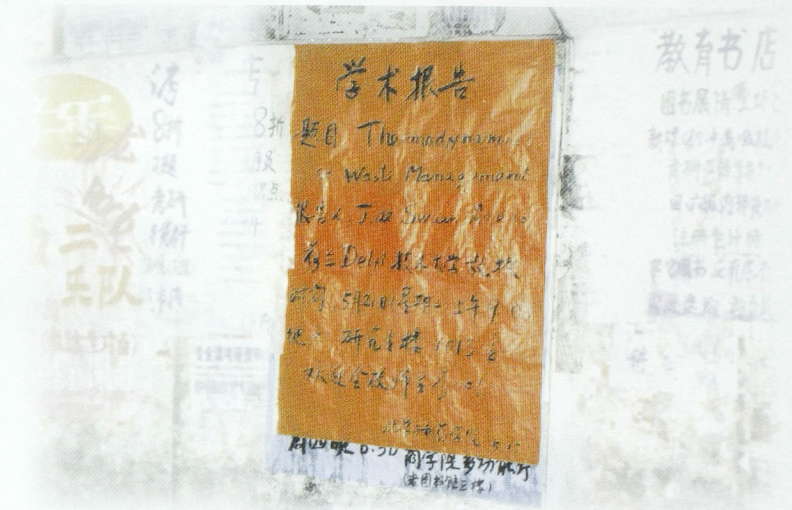
I am grateful to Astrid Barrow, my secretary of more than 15 years, for everything she has done for me: the many letters she has written, the presentations she has helped to prepare, the numerous phone calls she has made on my behalf, the trips she has arranged, the patience she has shown, the advice she has often given. Apart from my wife, no woman knows me as well as Astrid, my strengths and weaknesses, my successes and failures. But she will not tell you because she is a professional.



Picture 20. *Et Dieu créa la femme. The art of creation*

Finally I wish to thank my wife Kozue, Picture 20. Although she too is an active professional herself and a loving mother to our son Yoshimitsu, she has always created an atmosphere in which we could be happy together, both at home and on our numerous trips abroad. Kozue has always stood by me during my time in Delft and is a prime example of selflessness, a great virtue that, in my experience, is possessed by only a few. It is thanks to her

that I have discovered so many beautiful things about the Far East, its people and culture. And part of my future may well lie there. Picture 21.



Picture 21. *Announcement on a wall of the East China University of Technology in Shanghai, May 2002*