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for a sustainable future

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17528

Nov./Dec. 1988
ENGLISH

POLLUTION CONTROL RESEARCH INSTITUTE

DP/IND/83/008/11-02

REPUBLIC OF INDIA

Technical Report*

Prepared for the Government of the Republic of India
by the United Nations Industrial Development Organization
acting as executing agency for the United Nations Development Programme

Based on the work of Dr. Albert Mayer
Expert in Industrial Wastewater Treatment

Backstopping officer: R. Williams, Industrial Operations Technology Division

United Nations Industrial Development Organization
Vienna

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I FOREWORD

The job description outlined by UNIDO is as follows :

DP/IND/83/008/11-02

POST TITLE : Expert in Industrial wastewater treatment

DURATION : 1 month

DATE REQUIRED : November 1988

DUTY STATION : New Delhi & Hardwar (2 weeks) India, and home base (1 week for preparation of paper)

PURPOSE OF PROJECT : To hold an international conference on environmental impact analysis for developing countries sponsored by the Pollution Control Research Institute Bharat Heavy Electricals Limited, Hardwar , India.

DUTIES :

- 1 - The expert will present a paper on the application of recent developments in Industrial Wastewater Treatment Technology covering modern designs, application in the utility and industrial sectors and performance of modern installations. The paper will also discuss the potential of new innovative technology to meet the requirements of Developing Countries from the standpoints of :
 - Reduction in pollution of natural watercourses
 - Investment requirements
 - Operation and maintenance
 - Efficiency
 - Energy consumption
(and such other criteria as the expert considers necessary)
- 2 - The final paper should not be more than 15 pages of double-spaced typing including tables and diagrams.

One copy of the paper should be submitted to each of the following addresses by 30 October 1988.

- a) Head, Pollution Control Research Institute, B.H.E.I. Ranipur, Hardwar - 249403, U.P India
- b) R.O Williams, Industrial Development Officer, Chemical, Vienna, Austria.

3 - The EIA conference will be held in New Delhi 28 November to 2 December 1988. In addition to presenting a paper, the expert will participate in discussions covering environmental impact assessment in general.

4 - The balance of time for the mission will be used to provide technical assistance to P.C.R.I, Hardwar and for preparation of the paper and such visual aids as may be required. Information on visual aids requirements should be included with the papers as submitted per paragraph 2 above.

QUALIFICATIONS :

Physicist or Chemist with Higher degree and extensive experience in analytical techniques applied to ecological modelling.

LANGUAGE : ENGLISH

BACKGROUND INFORMATION :

India has reached significant levels of activity in various industrial sectors and the adverse effects on environmental quality are becoming apparent.

In recognition of the need for a comprehensive environmental policy, the Government of India instituted a high level committee, which submitted its report to the Prime Minister in 1980.

On the recommendations of this committee a separate department of environment (DOEN) was set up to take direct administrative responsibility for the control of environmental pollution and for co-ordinating the environmental related programmes in all sectors.

In the 6th Five Year Plan (1980- 1985), the Government of India stressed the need for an integrated approach to find out and implement methods of alleviating existing environmental problems and to build capability for preventing those that could arise in future. To meet these objectives a provision of R400 mil was made available in the 6th Plan. The approach paper for the 7th Plan (1985 - 1990) lays still greater emphasis on the research efforts in the pollution control area and a substantial increase in the financial allocations for research is envisaged

The state owned BHARAT Heavy Electrical Limited (BHEL) is already the largest producer of air quality control equipment such as cyclone separators and electro-static precipitators. B.H.E.L has made advances in several pollution control technologies.

An Industrial Pollution Control Research Institute is established by BHEL as its Hardwar complex.

The stay in India has been pleasant and well organized and the merits are to be shared by all the officials. The kind help and guidance of the following executives is appreciated :

- Mr. M. RAMACHANDRAN, UNDP, Delhi.
- Mr B.P GUPTA, India International Centre.
- Mr S.B.C AGARWALA, Head, PCRI.
- Mr A.K GUPTA, Manager, PCRI.
- Dr N.C TREHAN, Dy Manager, PCRI.

2 - ASSIGNMENT SCHEDULE**1 - HOME BASE****August and September 1988**

2 weeks - scrutiny of 207 abstracts sent by P.C.R.I -
B.H.E.L, Hardwar

October 1988

2 weeks - Completion of laboratory investigations and
preparation of paper to be presented at the International
Conference on Environmental Impact Analysis (EIA) for
developing countries - New Delhi, November 28 - December, 2
1988

2 - INDIA**Friday 25 November 1988**

Departure From Montpellier
Arrival Paris
Flight to Delhi

Saturday 26 November 1988

Arrival Delhi

Sunday 27 November 1988

Preparatory work for Conference

Monday 28 November 1988

Attendance International Conference, Delhi

Tuesday 29 November 1988

Chair Session III
Address of key note paper

Wednesday 30 November 1988

Rapporteur Session VII

Thursday 1 December 1988

Attendance International Conference

Friday 2 December 1988

Attendance International Conference

Saturday 3 December 1988

Left Delhi
Arrival Hardwar same day

Sunday 4 December 1988

Meeting with CTA and other UNIDO experts

Monday 5 December 1988

Consultancy work at P.C.R.I

Tuesday 6 December 1988

Consultancy work at P.C.R.I
Lectures

Wednesday 7 December 1988

Review of fundamentals
Study of projects

Thursday 8 December 1988

Consultancy

Friday 9 December 1988

Left Hardwar
Arrival Delhi same day

Saturday 10 December 1988

Various formalities in Delhi

Sunday 11 December 1988

Left Delhi
Arrival Paris

3 - TOPICS

The following topics were examined at P.C.R.I, Hardwar.

- Work related to design, and experimental studies at laboratory scale for high load wastes using anaerobic process.
- Studies on coagulation and flocculation
- Work related to the Khaperkheda TPS project
- Principles of industrial toxic wastes
- Advances in water pollution control field
- Protection against corrosion and scaling

4 - SPECIAL MEETINGS**Monday 5/12/1988**

Meeting with Mr R. MAHESHWARI
Mr P.K JAIN
Mr A.K MANUWAL

Tuesday 6/12/1988

Meeting with Mr R. MAHESHWARI
Mr B.K BEHERA
Mr P.K JAIN
Mr A.K MANUWAL
Mr S.PAL
Mr V.KUMAR

Meeting with Dr A.K BISWAS, CTA
Dr B.LOCKE
Pr P.WRAMMER
Dr K.FEDRA
Dr S.C WALLIN

Wednesday 7/12/1988

Meeting with Mr R.MAHESHWARI
Mr P.K BEHERA
Mr P.K JAIN
Mr A.K MANUWAL
Mr V.KUMAR

Thursday 8/12/1988

Meeting with Mr R. MAHESHWARI
Mr A.K MANUWAL
Mr P.K JAIN
Mr P.K BEHERA
Mr V.KUMAR

5 - RECOMMENDATIONS

VISIT OF INDUSTRIAL PLANTS

It is not possible to study seriously any scheme of industrial wastewater treatment unless the following steps are first accomplished :

- Thorough knowledge of the basic principles of physical and chemical phenomena
- Full understanding of the manufacturing process involved in any industrial plant
- Mean and peak values of the pollution load and toxics in the effluents
- Origin of the pollution
- Means of "in situ" abatement prior to any treatment

The best way to train the P.C.R.I staff is to encourage the project leaders to visit as many industrial plants as possible.

ACQUISITION OF NEW BOOKS

As useful guides to the above mentioned suggested visits, the following books are recommended :

- 1 - NORDELL E
Water Treatment for Industrial & other uses
Van Nostrand Reinbold Co.
New York
- 2 - D.J De RENZO
Unit Operations for the treatment of hazardous
Industrial Wastes
NDC Park Ridge, N.J, USA
- 3 - D.W HENDRICKS
Environmental Design for public projects
W.R.P POB 2841, Littleton,
Colo. 80161 - 2841, USA

LABORATORY EQUIPMENTS

We reiterate the need for the following items :

1 - Micromanipulator

LEITZ

Estimated at DM 32.000

2 - X Ray Fluorescence Analyser

LAB - X 2000

OXFORD Analytical Instruments

20 Nuffield Way

Abingdon

Oxon Ox 14 ITX

ENGLAND

TLX 83621

3 - TDS Analyser

Model L 87123

0 - 5 000 ppm

Price = 1378 French Francs

Bio Block

B₂ 111

6 403 ILLKJ RCH Cedex

Tel : 88.66.40

FRANCE

4 - New Elektra B.O.D Incubator

Portable B.O.D Incubator

S.A Associates

House of Industrial Testing Instruments

7/17 ROOP NAGAR, DELHI - 110007

Phones : 2917929, 29113605

6 - ANNEXURES

- Hazardous substances management program
H.I.T Cambridge, Mass, USA
- Solar Desalination -
Cadarache Nuclear Research Center, France
- Seawater and brackish water desalination
Cadarache Nuclear Research Center, France

W. Cherkov

20 December 1983

(continued from previous page)

are also needed to deal with huge amounts of existing contaminated soil and waste materials. Fundamental research into combustion processes are helping better understand the ways in which toxic materials are created by incomplete burning. Researchers believe that new ways to burn material more efficiently will result. Work in the policy area will examine the risks and tradeoffs involved in such new control technology. The overall goal is to create reliable and efficient systems which meet societal demands for destruction techniques.

Fate and Transport

In modern times, considerable quantities of hazardous materials have been introduced into our environment. Some toxic materials are unavoidably introduced even now, such as SO₂ and NO_x gases from combustion operations, although efforts are under way to reduce them. The Department of Civil Engineering has chosen to focus on groundwater research, explains Professor David Marks, head of this portion of the Initiative. Critical research areas include understanding movement of water through porous aquifers, sorption characteristics and kinetics of contaminants in soil and water, and transformations—from microbial action, for example—that occur to contaminants during sorption and transport processes.



Photo: Donna Courtney

As part of the effort to predict and control the movement of hazardous substances in the environment, Professor David Marks oversees studies on how these materials move through earth, air, and water.

Work involves understanding the chemistry of soil and the fluid mechanics of movement within it, as well as new instrumentation, monitoring, and modeling technology to observe and predict future pathways of contaminants. Work in the Department of Mechanical Engineering is focused on studying the way gas plumes from smokestacks at power plants are dispersed over the downwind terrain, in an effort to better predict the transport of acidic gases.

A key overall goal of the Initiative is to work on both theory and practice by bringing together researchers from academia, government, and industry.

Health Effects

This area, unique to the MIT effort, is headed up by Professor William Thilly, Director of the Center for Environmental Health Sciences. According to Thilly, the critical question debated in much recent litigation has been whether or not chemicals released or dumped into the environment eventually made their way to households or the workplace, through the water or air supply for example, and



Photo: Donna Courtney

Standing amidst a maze of equipment for analyzing fuel combustion, Professor Adel Sarofim explains how research he is coordinating focuses on technologies for limiting the production of hazardous substances and limiting their introduction into the environment.

caused cancer or other health problems in the plaintiffs' families. Work in the health effects area will attempt to provide a scientifically defensible rationale for adjudicating such cases. The issues to be studied include:

- Determination of what chemicals actually exist in complex mixtures of potentially hazardous substances and which are biologically undesirable.
- Development of methods to measure the amounts and types of chemicals which can enter the human system and their movement within the system.
- Study of techniques to identify and catalog small amounts of unknown chemicals in human systems.
- Investigation into exactly what happens on a genetic level to cells and DNA when such exposure occurs. MIT researchers have been working, for example, on a technique to establish a genetic "fingerprint" which marks an individual's exposure to specific materials. This information is critical to risk assessment and public policy making, and for setting limits for worker and citizen exposure. The work will provide data on exactly

what happens to the genetic material of cells when exposed to potentially dangerous substances.

Public Policy and Negotiation

This effort will overlap into all other areas of research in attempting to realize three goals. One is to devise a straightforward and comprehensible framework for making siting and other environmental decisions. The second goal will be to propose liability reform; such change is required to ensure adequate clean-up of existing sites and to prevent the actions of the past again. Third, researchers will develop frameworks which encourage participants involved in environmental disputes to jointly research facts and data necessary to reach compromise. Professor Lawrence Suskind of the Department of Urban Studies and Planning, an expert on negotiation and leader of this effort, explains that such a structure will lay the groundwork for negotiation, compromise, and progress in a variety of controversial issues.

The work will encompass not only research into negotiation, but also work on siting activities which will involve the MIT Center for Real Estate Development, and liability and tort issues, which will incorporate work done in the Sloan School of Management. The Center for Technology, Policy, and Industrial Development will also contribute to better understanding of ways to implement research findings in real settings. This effort is coordinated by Professor Daniel Roos, Director of the Center.

A key overall goal of the Initiative is to work on both theory and practice by bringing together researchers from academia, government, and industry. Research will not only attempt to develop new knowledge, but also seek to apply it in real cases to study. The steering committee of the Hazardous Substances Group, composed of the five faculty mentioned above, is looking to industrial partners for advice, data, and direction on future activities.

In addition to research, a large portion of the Initiative will focus on education. A recent independent survey of 69 selected universities revealed that the academic community is ill prepared to deal with the problems of hazardous waste management, showing a general lack of breadth, limited course offerings, and inadequately trained faculty. To help

correct this, MIT educators are developing a graduate level interdisciplinary core curriculum that will allow graduate students to focus on environmental and health issues. This core program can be supplemented with relevant courses from a variety of departments. The idea is to expose students to policy and management issues as well as technical aspect of hazardous substance problems.

In the long run, the educational component of the Initiative may have the greatest impact. By training students to recognize the broader implications of



Photo: Donna Courney

Professor William Thilly, leader of research on the health effects of hazardous substances, is working on a novel technique for determining an individual's exposure to specific chemicals.

working with hazardous substances, and by providing them with the opportunity to focus their energies on this critical field, the groundwork can be laid for the solution of many of our society's existing problems. A sound education in hazardous substances can also prepare students to anticipate hazards that may arise from new products and processes, and to deal with them before they become a problem.

— Marc J. Chelmer

For more information on the above research, circle number 55 on the Publications order card.

Feature

The Hazardous Substances Initiative: Working to Create a Safer Tomorrow

Advances in technology, especially in the last 100 years, have touched almost every facet of society. Improved pest control and other farming methods, for example, have set new standards for agricultural productivity. Modern equipment and techniques have made heat, light, and power readily available in every developed country in world. New chemicals and chemical techniques have made life more convenient in myriads of ways: better medicines, new kinds of clothing, more efficient household cleaning agents, fresher foods, and versatile new materials. Semiconductors, and the products they make possible, are revolutionizing the flow of information. And biotechnology holds the potential of further advances in fields as diverse as pharmaceuticals, agriculture, and energy.

But most of these advances have brought new risks as well. Many pesticides, for example, are harmful to beneficial insects and other animals, and eventually find their way into drinking water. Coal and oil combustion, essential to a wide variety of industrial processes, can pollute the air. Some additives that enhance the flavor or shelf-life of foods have been determined to be carcinogenic. And chemical and semiconductor production processes involve hazardous gases, liquids, or solids which must be contained properly during use, and then stored or disposed of safely.

The cost of dealing effectively with these substances, and the problems they can cause, is staggering. Just last year, U.S. industry alone spent an estimated \$46 billion on pollution control. Government, industry, and taxpayers spent billions more on developing and implementing laws and regulations, lobbying, litigation, and public awareness campaigns. Yet unless society can devise creative ways to address the complex problems of hazardous substances, the very quality of life that has been made possible by technological advance will be threatened.

Now, with the support and active participation of industry and government,

MIT has embarked on a major new research and educational initiative to address the national problem of hazardous substances. This effort is one of MIT's top priorities for the next decade. As a reflection of the extraordinary complexity of the problem, the program will draw on experts from MIT's Civil and Chemical Engineering Departments, the Energy Laboratory, the Department of Applied Biological Sciences, the Department of Chemistry, the Department of Urban Studies and Planning, the Center for Environmental Health Sciences, the Center

Hazardous materials can exist as gases, liquids, or solids; the specific nature and degree of the threat they can pose to health and the environment can vary broadly; and they are everywhere.

for Technology, Policy, and Industrial Development, and the Sloan School of Management.

One of the main goals of the new program is to integrate the expertise of these disciplines in order to build a rational framework for dealing with this pervasive problem. Working closely with industry, the MIT team hopes not only to make technological breakthroughs, but also to come up with effective management and policy strategies for implementing them. By strengthening and focusing its undergraduate and graduate educational programs in this area, MIT will also provide students with the proper combination of skills and insights needed to develop and implement further technological advances safely and efficiently.

Developing effective schemes for managing hazardous substances is particularly problematic because these materials can exist as gases, liquids, or solids; the specific nature and degree of the threat they can pose to health and the en-

vironment can vary broadly; and they are everywhere. As a result, progress in the field has been slow.

Often, the dangers posed by using these materials are not evident for a long time. It took years before the side effects of such substances as DDT, Agent Orange, and PCBs were discovered. Recent studies have shown that even ordinary used motor oil may be carcinogenic. In fact, a wide variety of readily available household products are dangerous, and should be handled—and disposed of—with care.

The problem is further complicated by the fact that the specific effects of exposure to chemicals are not clearly understood, and the technology and science of determining the long-term effects on living things of exposure to various substances is inexact at best. The resulting controversies and legal battles have served to cloud the basic issues at hand.

Finally, most existing methods for addressing the broad concerns about hazardous substances have evolved piecemeal in response to each problem as it has flared up. The research, regulations, and legislation that has followed the discovery of each problem has rarely been integrated and coordinated effectively.

Organizers of the MIT Initiative believe that an interdisciplinary approach is essential to progress in dealing with hazardous materials because of the variety of dimensions found in any particular problem. A company worried about coal combustion must, for example, consider the economics of alternative fuels, the technical possibilities for limiting the release of harmful gases and particulates, the way combustion products released to the atmosphere are dispersed, the health effects of the pollutants, and the political and regulatory environment.

Leaders of the Initiative also believe that an institution such as MIT can offer a "neutral ground" for addressing the more sensitive and controversial issues surrounding hazardous substances. Recommendations and research results may

achieve greater credibility when they come from an independent third party.

In order to help keep the research and educational aspects of the initiative relevant to the needs of society, MIT researchers are actively seeking the aid and advice of industry and government. A variety of collaborative and case-specific research programs will be set up to incorporate the industrial perspective. While these research activities will be coordinated by the MIT Hazardous Substances Group, which consists of representatives from several key areas of MIT, an advisory board of industry and government leaders will assist in setting the Group's agenda.

MIT has a long history of involvement in various facets of hazardous substances research. The Institute's very first recorded sponsored research project—which began in the fall of 1905—was for work on hazardous waste. According to a report released at the time, MIT received \$5,000 for "experiments with a view to finding out the cheapest and most efficacious way of purifying sewage before it is poured into the rivers and harbors of our country."

Over the years, a number of lines of investigation related to the management of

The Institute's very first recorded sponsored research project—which began in the fall of 1905—was for work on hazardous waste.

hazardous substances evolved independently throughout the campus. The new MIT initiative will bring this work together in an organized interdisciplinary framework. Dr. John Ehrenfeld, who has worked on environmental issues both in government and in industry for several years, has come to MIT as a senior research associate in the Center for Technology, Policy, and Industrial Development (CTPID) to hold this framework together as Program Coordinator.



Photo: Donna Courtney

An expert on negotiation, Professor Lawrence Sankind heads up efforts to develop rational frameworks for resolving environmental disputes and implementing public policy.

The Initiative will be loosely divided into four principal subject areas for research, as summarized below. Each effort will be coordinated by a senior faculty member. In each case, short-term goals will focus on specific technologies which could be applied to critical problems currently facing society. Long-range goals are directed towards providing new techniques, both technical and political, for addressing problems of the future.

Sources and Control

The purpose of this group, led by Professor Adel Sarofim of the Department of Chemical Engineering, is to study the sources of chemicals in our environment and how technology can reduce the risks they pose. The best method of dealing with some hazardous substances in the future is to not make them at all. But when they are created, techniques must be found to remove them as completely as possible before they reach the environment. Research in the Department of Chemical Engineering is under way on both these subjects. On the topic of prevention, alternative pathways in chemical manufacture which could be used to create desired products while reducing wastes or unwanted byproducts are being investigated

Other work focuses on examining computer models which can assist process engineers in maximizing product output while minimizing waste production. Advanced computer systems to monitor operations, predict failures, and assist plant operators in emergency situations in process plants are being developed. Such systems could prevent exposure of workers to hazardous materials, and minimize accidental release of materials into the environment. Such tools will help prevent nuclear or chemical plant accidents in the future, and instill confidence to local communities that nearby plants are indeed safe.

The technology for destroying existing hazardous materials is another major research thrust. Supercritical oxidation of chemicals promises an efficient means to destroy ammonia, carbon monoxide, and organic materials. Incineration technology has reached the point where 99.9999% of materials introduced into a furnace are burned to harmless residues, CO₂, and water. Ongoing work is directed towards developing high-speed sensor systems to accurately monitor and control such incinerators as the feed-stream contents change. Better systems

(continued on next page)

**THE MIT PROGRAM ON
HAZARDOUS SUBSTANCES
MANAGEMENT**



**PARTNERS FOR A SAFER
TOMORROW**

Why

The management of chemicals in the environment, broadly construed to include products with beneficial uses and pollutants arising from a variety of sources, is a problem that pervades the national economy and political agenda. It has persisted as a high priority issue in every broadly based public opinion survey over the last decade or more. Billions are being spent to clean up old wastes and to manage current outputs. Federal regulatory activities run at a frenzy. Government and private research probe the causes and solutions to the problems at a variety of different institutions.

Even with all this effort there has been little progress in recent years. The currents are running the wrong way, and as a nation we are locked into a gridlock of conflicts. We cannot agree on priorities at the national policy level. We cannot agree on the scientific basis for action. We cannot agree, at the local level, on the siting of long overdue, safe facilities. New approaches are clearly needed.

Program Concept and MIT's Role

MIT, with support and cooperation of industry and government, has made a major commitment to help solve the complex problems of chemicals in the environment through our comprehensive research and education *Program on Hazardous Substances Management*. The basic shape of the program, as described below, reflects the complex and demanding set of problems that must be addressed. It follows a new approach, predicated on the unique resources and reputation of MIT.

New Paradigms

The stalemate that accompanies both debate and action around this complex set of problems continues. While more resources are needed, simply working harder is not enough. We believe that the approaches and techniques needed to solve this set of problems must be *different*, not merely better. That is, we need new paradigms—models or frameworks that shape the way we see the world and take individual and collective actions. Our faculty, through their research in many areas, have already brought us to the frontiers of critical, new paradigms.

Technology Linked to Policy

We have seen that the creation of better and better technology is not the same as securing the social acceptability of the application of that technology to solve a particular problem. The technology development process must be coupled with new techniques to allow the parties involved to resolve their differences, to determine what is to be demanded or expected from the technology, and to create an opening for action and progress.

Scientific knowledge and technological practices must be linked to policies which can extract the benefits intrinsically available in that knowledge and set of practices. Current policy-making and decision-making procedures have effectively shut down the conversations that must occur in our society to reach such a desirable state. Technical research must go hand in hand with investigation into new decision-making tools and with examination of alternative policy options. Our proposed research agenda and educational program strive to forge these links.

Multidisciplinary

The problems are extremely complex, involving scientific, technological, and social policy questions. Although parts of the puzzle can be fitted by solutions resting within a fairly narrowly defined discipline, the tougher issues will not be resolved without substantial interplay among several areas. For example, research leading to a fundamental understanding of the health effects of hazardous substances, as we have approached that question at MIT, has closely coupled research in applied biological sciences, chemical engineering, and analytic chemistry to achieve a level of understanding not available through isolated endeavors.

The program is structured as a matrix organization to promote maximum intermingling of the large base of on-going research activities and new projects created out of this initiative, and draws on the expertise of specialists in the fields of

- the destruction of hazardous wastes
- the containment of wastes at old disposal sites
- process changes to avoid the generation of hazardous substances
- movement of chemicals through the environment
- toxicology and human health effects
- risk assessment
- monitoring, instrumentation, and inspection techniques
- mediation of science-intensive disputes
- regulatory law and economics.

MIT's Commitment

The large academic institutions have a critical role to play in resolving this and similar large societal problems. The traditional, somewhat passive role that is taken by many academic institutions with respect to the choice of priorities often leaves them playing catchup with the problems out in the world. This is not the case here; MIT has, through commitments by the faculty and by the top administrative officers, made the management of hazardous substances one of the highest priority areas for research and education for the next decade.

Neutral, Objective Source of Knowledge

Academic institutions offer an additional characteristic no longer immediately associated with either government or business, that of neutrality and trustworthiness. By working in a university context, with its open inquiry and flexibility, the credibility of the research and the findings will be greatly increased.

Theory and Practice—Hand in Hand

MIT has since its inception built its institution on the concept of theory and practice, hand in hand, as our motto (*Mens et Manus*) states. This proposal follows in that mold. Our research plan will couple the basic elements to a set of integrated, applied projects that will spill out into the real world as our extended laboratory. This approach assures the building in of reality checks, particularly important in any program that seeks to couple science, technology, and policy.

Partnership

A successful program in this area must be based on cooperation, support, and guidance from all of the key groups of interested and involved parties. This program

integrates financial and intellectual support from industry with government research contracts to achieve a mix of activities not attainable from a single source.

Education and Technology Transfer

Successful research is of little use until its meaning, impact, and potential applications become known to and are accepted by society. Education and a continuing program for the transfer of the results must be closely integrated to the research agenda.

The Program Framework

One view of the overall program is depicted in Figure 1. This representation shows the three major programmatic elements—basic research, applied research, and education—and indicates their interlinked relationships. The initial plan has three long-term research objectives, to:

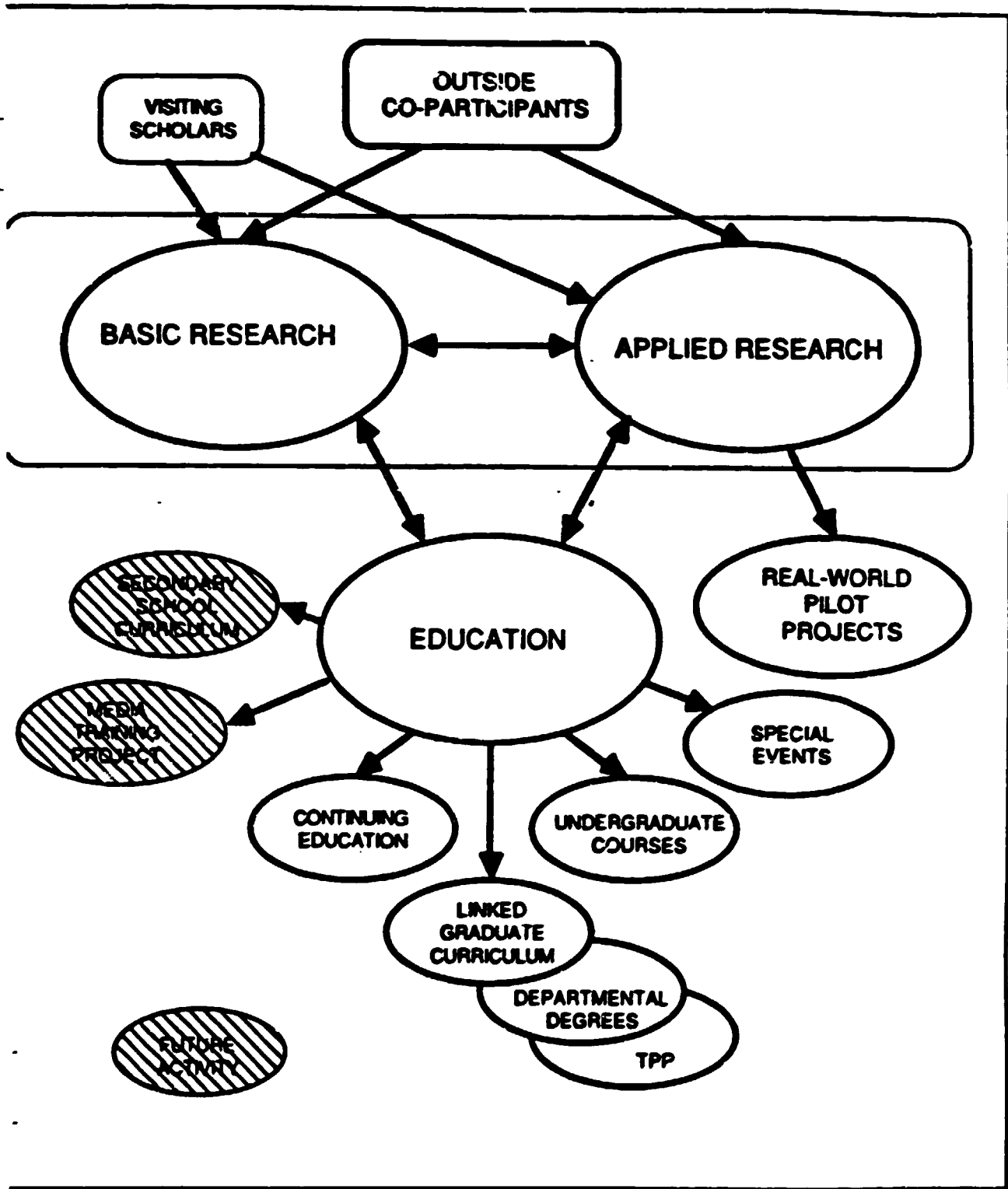
- develop new approaches to public and private decision making that can break the present logjam surrounding siting, regulation, and policy making in this area generally (The shift comes in the replacement of technocratic, bureaucratic, top-down approaches to policy and conflict resolution by a consensual, participatory approach to policy development and conflict avoidance);
- develop new methods to provide direct evidence of the effects of chemical exposure on human health which will permit wiser setting of priorities, technological choices, and objectives for risk management (The change replaces an inferential basis fraught with uncertainty and inherent judgments with a more scientifically-defensible system);
- develop innovations in product and process technology that will help us avoid the creation of wastes and dangerous products in the first place (The shift is obvious; from waste management to waste reduction and elimination).

In addition, reflecting the need to provide better interim, short-term approaches, we also seek to

- develop more acceptable, safer waste management technologies to handle the wastes of the past and present, for example, large quantities of contaminated soils for which there few practical and economical current techniques available; and
- develop better understanding of the fate and transport of chemicals in the environment to reduce the uncertainty in risk assessments and in selecting site-specific solutions.

We expect short-term needs to shift continually over time, and, with the guidance of an outside steering committee, we will adapt our research agenda accordingly.

The concomitant educational thrust is to develop a strong program for both undergraduate and graduate students to assure that future public and private leaders will be knowledgeable about hazardous substances and will be able to lead us toward a safer tomorrow. Through specialized courses and curriculum development, we will extend the activities outside. MIT has a very strong record of curricular innovation which has influenced the teaching of many disciplines nationwide.



HAZARDOUS SUBSTANCES PROGRAM—BUILDING BLOCKS AND LINKAGES

FIGURE 1

Both the research and educational elements of the program are built on four broad areas of inquiry:

1. What are the sources of chemicals in our environment and how can technology reduce the risks they pose?
2. How do hazardous chemicals move through and become modified by the environment?
3. What are the relationships between these chemicals and human health or environmental degradation?
4. What kind of policies and decision making will lead to levels of risk that are acceptable to all sectors of our society?

The Educational Elements

The educational direction of the hazardous substances program is designed to have a long-term impact. MIT educates scientists, engineers, managers, and designers of public policy who will shape our future. The primary educational objectives are to allow graduate students an opportunity to focus on the problems of hazardous substances and to give undergraduates an informed perspective from which to view the the implications of their technical work.

An interdisciplinary core curriculum for graduate students in otherwise separate MIT departments and centers emphasizes environmental, and health issues. Graduate students doing specialized work in a conventional disciplinary framework on some aspect of this problem develop a working knowledge of related technical and policy issues. In addition to the core curriculum in hazardous substance management, they take related courses available through regular departmental offerings.

The first four courses, all with a common theme to draw attention to their interconnected nature, will be offered for the first time by the end of the 1987-1988 academic year. They are (the first time is in parentheses):

- Chemicals in the Environment: Sources and Control (Spring 1987)
- Chemicals in the Environment: Fate and Transport (Fall 1987)
- Chemicals in the Environment: Human Disease (Spring 1987)
- Chemicals in the Environment: Policy and Management (Spring 1988)

Additional subjects need to be developed on related aspects of hazardous substances management to permit students in degree programs to gain specialized skill and understanding. Taking this series of courses will provide a context for the graduate's future career and may lead some students directly into professional activities involving hazardous substances. The program is being designed primarily to fit into the existing degree structure in the departments whose graduates would most frequently become involved with hazardous substances management. At MIT the departments include Civil Engineering, Chemical Engineering, Applied Biological Sciences, and Urban Studies and Planning.

It is expected that students who wish to leave with a subspecialty in this area will take the above sequence of courses and will do theses on related subjects. In addition, some students may choose the Technology and Policy Program (TPP) leading to the Master of Science in Technology and Policy which provides a strong foundation in advanced technology combined with graduate level training in economics, political science, and the social sciences.

The program will offer, in addition to the MIT academic activities, seminars, summer programs in specialized areas, and other continuing education projects. A periodic newsletter is planned.

The Research Elements

Current projects related to hazardous substances (see Appendix A) are running at an annual budget of over \$6,000,000, and are sponsored by a variety of sources including the EPA, NIEHS, DOD, DOE, state agencies, and industrial grants. The research program is focused on those pressing problems where MIT experience and capabilities are most relevant. In some of the areas, on-going work promises breakthroughs on how we understand and deal with the hazards of chemicals in the environment.

Important loci for the types of research and teaching emphasized in the program presently include the departments of Civil Engineering, Chemical Engineering, Applied Biological Sciences, Chemistry, and Urban Studies and Planning; the Energy Laboratory; the Center for Environmental Health Sciences; the Center for Technology, Policy, and Industrial Development; and the Sloan School of Management.

The following areas include current research and planned new projects.

Laboratory-based Research Themes

Incineration and Other Advanced Technologies—Research on fundamental combustion processes at MIT has achieved a level of understanding and sophistication sufficient to apply to the particular problems of hazardous waste treatment. Incineration is a key technology, but must still be improved before it finds widespread acceptance. New studies planned for the program include elucidation and control of processes that form incomplete products of combustion, analysis of failure modes and system malfunctions, relationship of destruction mechanisms to thermochemical and mixing processes, and the development of high-speed response performance monitoring instrumentation. The latter is particularly important, as fail-safe operational control has been found to be a critical element in the concerns of opponents to facility siting.

A high priority project will examine incineration and other advanced technologies as a means to treat contaminated soils, perhaps the most difficult and expensive problem associated with clean-up.

Work in this area builds on a large faculty and laboratory base. Pilot and full-scale combustors are in place in the Energy Laboratory and the Chemical Engineering Department. A large body of past and current work on understanding the toxicology of combustion products strongly couples two of the four programmatic themes, sources and control and health effects.

Human Health Effects—This part of the program integrates much research in progress. One aspect involves dissection of complex chemical mixtures such as found in most hazardous substances and in the wastes at abandoned disposal sites, and determines the individual chemical components responsible for the undesirable biological activity of the mixture. A major new effort now underway involves the direct measurement of the amount and kind of chemicals that enter a human under normal environmental conditions, and the determination of which, if any, have undesirable effects. The techniques permit analysis of known compounds in blood samples, but additional research is needed to improve analytic sensitivity to permit identification of unknown substances. A third area seeks ways to diagnose the causes of disease by examining the patterns of genetic change in blood cell samples.

These interrelated endeavors are strongly supported by individual and program/project grants in the Center for Environmental Health Sciences (Departments of Applied Biological Sciences, Chemical Engineering, Chemistry, Civil Engineering, and the Energy Laboratory). Advances in this area will profoundly affect the ways we set standards, adjudicate tort cases about toxic substances, and monitor the health of large populations.

Fate and Transport of Chemicals in the Environment—Knowledge in this area is essential to forging the links between sources, human and environmental receptors, and the controls that must be used to manage risks. Again building on a large body of existing expertise and laboratory resources, the program will include studies on improved models for predicting movement of contaminants in groundwater, soils, and sediments. The work will couple physics, chemistry, and microbiology. Mathematical models are needed in a variety of applications, ranging from policy analysis to risk assessment to site-specific design. Field studies, although expensive, are critical to perform in order to validate the models and demonstrate their effectiveness. Field-monitoring instrumentation will be developed in another project aimed at the problems of measuring contaminants in soils and groundwater.

Policy and Case Study Themes

Environmental Policy and Dispute Resolution—Policy and management research will focus on the basic research objectives over the next five years. The first concerns the institutionalization of negotiated approaches to siting facilities and to making other decisions with environmental implications. There are many federal and state agencies who are interested in cooperating in research in the field in order to find better ways to manage their responsibilities. Particularly with regard to clean-up, the institutionalization of negotiated approaches can save time, money, and perhaps even lives.

The second objective is to examine potential reforms to the present liability system. Such work is key to resolving fundamental problems in both the remedial context and in avoiding expensive conflict in the future. The third part will look at methods for joint fact finding and for resolving science-intensive disputes. In some instances, MIT researchers could play a neutral fact-finding or mediating role in actual cases.

Impact of New Science and Technology—The implementation of research results from MIT and other institutions will, in many cases, have large impacts on current regulatory policy and administrative practices. In anticipation, the program will develop and examine new policy options. For example, it was noted above that knowledge derived from health effects research will change the way we set priorities and treat other critical aspects of toxics policy. Advances in waste treatment and clean-up technology will have similar impacts on standards setting and on monitoring requirements. Projects to examine the implications of the health effects work and to investigate the acceptability of incineration, as a key treatment technology, have been assigned high priority.

Transportation—The transportation of hazardous substances is one of the most risky parts of the flow of chemicals in the environment, and is a key economic factor in hazardous waste management. Evaluation of logistical systems for pick-up and transport of wastes from dispersed sources will be an important element of the household project described below.

Management of Household Hazardous Wastes—With the urging and support of Governor Sununu of New Hampshire to use that state as a case-to-study, we are planning a project to develop and assist in the implementation of a state-wide household hazardous waste management system. Our research objectives extend far beyond simply putting into place a periodic collection program. We will determine the way that individuals perceive the risks in using and disposing of these materials, and examine the short- and long-term risks to the entire community. The choice of technologies, particularly incineration, scaled to the dimensions of this problem, relative to industrial waste, will be made in a policy dialogue and conflict resolution framework based on the mediation techniques developed by Professor Lawrence Susskind. By carrying out the project with real issues, real institutions, and in real time, we will test the practical utility of the research applied

broadly. A secondary objective of this project is to learn how to educate the general public about the origins of hazardous substances and of their roles in both creating and managing the problems that arise.

Guiding the Program and Setting Priorities

Research activities are coordinated by the MIT Hazardous Substances Group which includes representatives from several different departments and centers at MIT. An advisory board of senior industry and government officials will meet frequently to assist the group in setting its agenda. The MIT initiative is structured differently from other school's programs. We have not established a new center or laboratory, but, rather, have designed our program around a matrix management concept in order to involve and benefit from the entire body of interested faculty and staff.

This initiative is the outgrowth of the commitment of a core group of senior MIT faculty to apply their research and academic pursuits to solving the problems posed by chemicals in the environment. The Hazardous Substances Group includes:

Prof. David H. Marks
Head, Department of Civil Engineering

Prof. Adel Sarofim
Department of Chemical Engineering

Prof. William G. Thilly
Department of Applied Biological Sciences
Director, Center for Environmental Health Sciences

Prof. Lawrence E. Susskind
Department of Urban Studies and Planning

Prof. Daniel Roos
Japan Steel Industry Professor of Civil Engineering
Director, Center for Technology, Policy, and Industrial Development

In addition to the core group, other faculty will participate in both the educational and research aspects of the program. Dr. John R. Ehrenfeld, who has spent over 20 years in both the public and private sectors working on environmental problem solving, has joined MIT to serve as coordinator of the overall initiative.

Financial Support

Support for the program for a safer tomorrow is expected to come primarily from two sources: industry and government. Support is also being sought from foundations. Government support will largely be directed to individual focused research projects and to the on-going activities within the Center for Environmental Health Sciences. We will seek joint funding for projects wherever appropriate.

Industrial sponsors fill key financial gaps. The primary areas of need include: seed research, policy-oriented case studies, outreach and continuing education, curriculum development, graduate student fellowships, and to underwrite overall project management. Fellowships are a critical need; approximately half of the industry support will be allocated to permanent fellowship endowment.

The base level of industrial support sought is a total of \$10,000,000 to fund the first five years of the program. To reach this goal, MIT is seeking contributions of \$1,000,000 spread over the five years, from each of 10 corporations.

APPENDIX 1

**SELECTED LIST OF CURRENT(1986-87)
MIT RESEARCH PROJECTS
RELATED TO HAZARDOUS SUBSTANCES**

Sources and Control

Organic Particulates from Vaporizable Fuel Combustion

J. P. Longwell, J.B. Howard, W.A. Peters, and A.F. Sarofim

Basic studies of organic particulates from vaporizable fuel combustion, focusing on characterization of soot and polycyclic aromatic hydrocarbon compounds (PAHs) produced by combustion of vaporizable fuels under well-defined conditions using relatively small-scale equipment, collection of soot and PAH samples, including sulfur- and nitrogen-containing polycyclics, for detailed chemical analysis and studies of toxicity. Relationships between mutagenic/carcinogenic activity and fuel/flame characteristics will be studied.

Organic Particulates from Coal and Heavy Liquid Fuel Combustion

A.F. Sarofim, J.B. Howard, and J.M. Beer

The formation of organic particulates and polycyclic aromatic hydrocarbons will be studied under well-defined laboratory conditions simulating the temperature and oxidation histories expected in practical combustors. Emphasis will be placed on pulverized coal, coal-derived liquids, and residual oils with high carbon/hydrogen ratios.

Health Effects of Combustion of Vaporizable Fuels

J.P. Longwell and J.P. Howard

Research addressing chemistry questions in the formation of soot and PAHs (polycyclic aromatic hydrocarbons) from the combustion of fuels that may readily be vaporized. The project may be conveniently divided into two facets. Well Stirred Reactor Studies (facet A) are based on use of a reactor designed to eliminate mixing effects by promoting intense stirring of reactants and products during the actual combustion process. Laminar Flame Burner Studies (facet B) employ relatively small-scale laboratory flames in which the flow of reactants is laminar and in which they are either mixed at low temperatures prior to reaction, or mixed together by molecular diffusion.

Analytical Chemistry for Combustion Products

K. Biemann

In a collaborative effort with the Department of Chemical Engineering and the Toxicology group of the Department of Applied Biological Sciences, the component of the complex products derived from the combustion of various fossil fuels are being identified by gas chromatographic mass spectrometry, high performance liquid chromatography, and Fourier-Transformation Infrared spectroscopy. This effort is directed towards minimizing the health hazards, if any, posed by the use of fossil fuels in engines and furnaces, by modifying the combustion process.

Formation of Polycyclic Aromatic Hydrocarbons in Premixed Flames

J.P. Longwell and J.B. Howard

Rich mixture flames form polycyclic aromatic compounds, some of which are mutagenic or carcinogenic. Formation of these compounds is being studied in a flat-flame burner and a jet-stirred reactor.

Molecular-Weight Growth in Flames

J.B. Howard and J.P. Longwell

Basic research on the chemistry of molecular weight growth in fuel rich flames and development of kinetic models to predict yields of desired and undesired products for reaction systems of interest. Special attention is on mechanisms of soot and polycyclic aromatic hydrocarbon (PAH) formation. A molecular beam sampling instrument and on-line mass spectrometry are used for in-flame measurements.

Aromatics of Oxidation and Soot Formation in Flames

J.B. Howard

A study of the kinetics and mechanisms of aromatics oxidation and soot formation in flames, using molecular-beam sampling with on-line mass spectrometry, analysis of beam deposits, and in-flame laser scattering and absorption. Profiles of soot particle size and number concentration and radical gas species concentration are measured and used in critical tests of reaction models.

Formation of Nitric Oxides in Flames

A.F. Sarofim and J.M. Beer

Experimental and theoretical modeling of the formation of nitric oxides in flames, the devolatilization of nitrogen-containing compound from coal and the oxidation of atmospheric and fuel nitrogen in both premixed and diffusion flames will also be studied.

Analysis of Polycyclic Aromatic Compounds

K. Biemann, J.E. Biller and J.J. Gagel

Analysis of polycyclic aromatic compounds produced in combustion engineering studies. Advanced techniques of gas chromatographic mass spectrometry will be used to identify the compounds present. A method of off-line coupling of high performance liquid chromatography and infrared spectroscopy is also being developed for this purpose.

Computer in Mass Spectrometry

K. Biemann and J.E. Biller

Development and improvement of hardware (interfaces between mass spectrometer and a computer) and software for the acquisition, evaluation, and interpretation of mass spectrometric data. These techniques are at the same time used in the investigation of organic compounds from biochemical, clinical, and environmental sources.

Combustion Research Facility

J.M. Beer, P.M. Walsh, M. Toqan and T. Yu

A program has been initiated on the clean combustion of fossil fuels (gas, oil, and coal) and new coal-derived fuels such as Low-Btu gas, solvent refined coal, coal-in-oil mixtures, coal-water slurries, and oil-water emulsions. Central to this program has been the design, construction, and operation of a pilot-plant size experimental furnace with up to 3 MW thermal input, with variable heat sink and multifuel burning capability. Combustion diagnostic techniques under development include laser soot scattering, laser velocimetry, and spectroradiometric measurements.

Combustion Studies of Health Effects of Particulates

J.M. Beer, W. Farmayan, D. Teare and P.M. Walsh

An investigation of the formation of organic particulates from industrial combustion. To understand this problem, turbulent mixing, heat transfer, and chemical kinetic processes occurring in industrial-size flames are being studied. Organic particulates including polycyclic aromatic hydrocarbons and sulfur and nitrogen-containing heterocyclic will be studied in pilot-scale combustion equipment, which allows the processes to be independently examined and their interactive effects to be understood.

Combustion Studies of Organic and Inorganic Particulates

J.M. Beer, P.M. Walsh, M. Toqan and A. Dutta

To fully understand the formation of potentially toxic particulates in practical scale combustion equipment, the turbulent mixing, heat transfer, and chemical kinetic processes in the flame must be carefully studied. The purpose of this project is to perform these studies in a controlled manner using pilot plant scale equipment that allows these three processes to be independently studied and thus their interactive effects to be understood. The focus is on turbulent diffusion flames and fluidized bed combustion.

Combustion Sampling for Chemical and Biological Characterization

W.A. Peters, A.G. Braun, A.L. LaFleur and J.P. Longwell

The objectives are to provide reliable samples of soot and organic combustion emissions for detailed chemical and biological analyses, and to relate the results of those analyses to combustion conditions and fuel type. Practical scale combustion equipment (such as the residential oil burner) and model combustion reactors are being examined.

Chemical Analysis for Combustion Research

A.L. LaFleur

A collaborative effort between the Energy Lab and the Environmental Health Sciences center to provide and maintain a Laboratory for the chemical analysis of fossil fuels and their combustion products. Work is under way to characterize combustion samples from a number of sources so as to shed light on the mechanisms of formation of species suspected to pose human health problems.

Chemical Analysis for Health Effects Research

A.L. LaFleur

Research to characterize a number of combustion-related complex mixtures, with special emphasis on the identification of agents responsible for mutagenic, carcinogenic, and/or teratogenic effects.

Kinetics of Oxidation of Ammonia, Carbon Monoxide, and Other Organic Compounds in Supercritical Water

J.W. Tester

Fundamental studies of the kinetic rates and mechanisms of oxidation of ammonia and carbon monoxide as a homogeneous reaction with oxygen in a supercritical water phase. The oxidation of other organic molecules is being examined in supercritical water as a method of hazardous waste treatment. Additional studies are also under way on oxidation methods of waste water treatment for spacecraft applications.

Gas Treating with Reactive Emulsions

T.A. Hatton

A technical and economic evaluation of a novel emulsion scrubbing process for the removal and/or recovery of trace solutes from gaseous streams.

Electroosmotic Control of Hazardous Waste Leachates

R.F. Probstein and P. Renaud

Laboratory tests and theoretical analysis of the feasibility of using electroosmosis at hazardous waste sites to control and direct leachates, injected fluids, and groundwater flow.

Eate and Transport

Stochastic Prediction of Dispersive Contaminant Transport

L.W. Gelhar

Development of methods to determine field scale dispersion coefficients and evaluation of the reliability of groundwater solute transport predictions of contamination plumes. Stochastic transport theory is being used to predict the concentration of variance in terms of hydraulic conductivity variability. Existing field data on plume dispersion is being compared with stochastic theory for macrodispersion and concentration variability. Applications to the design of monitoring networks and aquifer restoration are also considered.

Colloid-Enhanced Toxic Chemical Transport in Groundwater

P.M. Gschwend

Isolation, quantification, and characterization of colloids from contaminated groundwaters in addition to measurements of the sorption affinities of toxic hydrophobic chemical for these colloidal sorbents.

Biological Impact of Waste Metal Disposal

F.M. Morel and G. Harrison

An investigation of the physiological (and when necessary, biochemical) processes through which toxic metals affect the planktonic biota, how these processes depend on the chemistry of the medium, and how organisms respond to metal stress through acclimation, adaptation, or modification of their medium. Ultimately, a convenient and rapid chemical assay will be developed for determining the sensitivity of phytoplankton to trace metals.

Acid Deposition on a Massachusetts Water Supply Watershed

H.F. Hemond

A biogeochemical study of a central Massachusetts watershed, focusing on sources and sinks of major ions, links with subsurface hydrology, and biological processes.

Guided Wave Measurement Techniques

K.R. Maser

Development of instrumentation for improving *in situ* evaluation of containment barrier systems at hazardous waste sites using geophysical theories and methods.

Field-Portable Probe for Volatile Pollutants and Biogeochemicals

H.F. Hemond

Development of a lightweight, high-performance, field-portable instrument for detecting a wide range of volatile environmental pollutants and biogeochemicals to provide rapid on-site information to field workers on pollutants and biogeochemicals in a variety of coastal environments not measurable with existing techniques. Membrane interfacing and mass spectrometric detection will be used.

Field Instruments for Measuring Volatiles in Groundwater

P.M. Gschwend and H.F. Hemond

A project to facilitate groundwater monitoring of volatile organics by developing: (1) an on-column aqueous injective glass capillary gas chromatograph and (2) *in situ* membrane-probe mass spectrometer system for field use.

Water Quality Monitoring

H.F. Hemond

Developing an *in situ* probe which can be easily driven into aquifers or inserted into monitoring wells or surface water and will provide monitoring of volume organic contaminants such as solvents and fuels. The semi-permeable membrane technique will be used, and detection will be done by mass spectrometry.

Health Effects

Cell Cultures for Bioassay of Environmental Chemicals

W.G. Thilly, A.G. Braun and A.L. Lafleur

A multidisciplinary program to apply newly developed techniques utilizing continuously propagating human cell lines in assays for mutagenic and cytotoxic effects of environmental chemical on human cells.

Diagnosing the Causes of Human Genetic Disease

W.G. Thilly, N. Cariello, A. Cantiello and I. Gennett

Using human blood samples and the concept to mutational spectra, means are being developed to discover the causes of human genetic change.

Toxicology of Macromolecular Damage

J.M. Essigmann

Characterization of the molecular events that underlie the genotoxic effects of environmental chemicals. The experimental approach being developed utilizes the tools of organic synthesis and genetic engineering to construct DNA molecules that have derivatives of environmental toxins situated at exactly know genome locations. These DNAs are introduced into the cellular environment where they act as probes for detecting how the toxin residue changes the normal functioning and processing of DNA. Ultimately, it is the objective of this program to formulate rules that could make possible prediction of the genotoxic activity of environmental chemicals.

Genetic Toxicology Testing Laboratory

A.G. Braun

The laboratory interacts with numerous investigators both inside and outside MIT to assay large numbers of chemicals and complex mixtures to determine toxicological activity. Basically, gene locus mutation in bacteria or human cells is the end point examined. Research on assay development and improvement is also conducted.

In Vitro Teratogen Testing

A.G. Braun

A study of methods for the evaluation of teratogenic potential in complex mixtures. Exogenous metabolizing systems are being used to "activate" and inactivate teratogenic agents *in vitro*. The principal system in use involves the attachment of cells to lectin-coated surfaces. Most teratogenic agents interfere with attachment. A quantitative relationship between the concentration of inhibitory teratogens *in vitro*, and their teratogenic activity *in vitro* has been demonstrated for over 100 teratogenic agents. As appropriate, other *in vitro* teratogenic assay systems will be used in the laboratory.

Molecular Interactions in Carcinogenesis and Mutagenesis

G.N. Wogan, W. Rausch, and G.H. Buchi

Many chemically inert compounds can be metabolically converted in the tissues of animals and man into reactive derivatives. Covalent binding of these derivatives to cellular macromolecules, especially DNA, can give rise to various toxic manifestations including cancer, mutation or cell death. Similar mechanisms may underlie other forms of toxicity including teratogenesis, hemolytic anemia, and allergic reactions. Elucidation of these molecular interactions is therefore crucial to an understanding of the mechanisms underlying the toxic responses. Studies with this general objective are in progress on the following compounds: aflatoxins and sterigmatocystin; benzene; nitrosamines; heterocyclic products of coal combustion; and pyrolysis products of amino acids.

Carcinogen-Binding Proteins

M. A. Marletta, H. Barton, M. Constantini, and H. Kwon

A protein in mouse liver cytosol has been found that binds many polycyclic aromatic hydrocarbons in a receptor-like fashion. Studies will include purification, characterization, and determination of biological function.

Chemical Carcinogenesis and Activation of Cellular Transforming Genes

G.N. Wogan

Whole animal and tissue culture models have been developed to ascertain the sequence of events that follows a single-dose exposure of a chemical carcinogen. The temporal relationship between the formation of DNA-carcinogen adducts and the activation of proto-oncogenes to the development of a preneoplastic cell phenotype and the subsequent development of a tumor are being investigated. The activation of specific proto-oncogenes in response to particular compounds will be observed by measuring (1) the relative levels of oncogene-specific mRNAs, (2) the transforming potential of cellular DNA after transfection into mouse fibroblast cells, and (3) changes in sizes of oncogene-containing restriction fragments.

Modifications of Macromolecules by Products of Fossil Fuel Combustion

G.N. Wogan

Determination of biological effects of combustion products involving studies on modifications of macromolecules, *in vivo* and *in vitro*, by products of fossil fuel combustion. The goal is to predict the potential health hazards posed by compounds and crude extracts derived from fossil fuel combustion residues by determining the extent and nature of the covalent binding of the test compound to biological macromolecules. Compounds will include selected polynuclear aromatic hydrocarbons (including fluoranthene and others) representative of those identified in the extracts of soots formed under well-defined fossil fuel combustion conditions.

Human Chemical Dosimetry

S. R. Tannenbaum and P. Skipper

Development of analytical approaches to the monitoring of individual human exposure to exogenous chemicals, such as environmental carcinogens. The primary focus is on formation of stable adducts with blood proteins. Compounds under study include hydrocarbons, aromatic amines, aflatoxin, and N-nitroso compounds.

Nitrosamines as Environmental Health Hazards

S.R. Tannenbaum

Development of analytical methodology, coupled with studies of the metabolism of nitrate and nitrite, formation of N-nitroso compounds from food components, etiology of gastric cancer, and formation of nitrosamines *in vivo*.

Carcinogenicity of Fossil Fuel Combustion Products

W.F. Busby

Development of short-term animal bioassays for testing the carcinogenicity or tumorigenicity of compounds and soots derived from the combustion of fossil fuels. The emphasis has been placed upon the induction of lung tumors or their precursor lesions within a six-month period.

Policy and Management

Mediating Science-Intensive Policy Disputes

L. Susskind

An analysis of current efforts to mediate science-intensive policy disputes such as the siting of resource recovery plants, hazardous waste disposal, coastal zone description, and ocean dumping. The objective is to evaluate the effectiveness of mediation as a strategy for resolving such disputes. Recent demonstrations will be evaluated.

Superfund Enforcement

L. Susskind

Analysis of Superfund negotiations at 25 sites throughout the United States with the objective of identifying the barriers to negotiated settlements and suggesting to the EPA alternative approaches to resolving technical and political disputes over cleanup.

Environmental Mediation

L. Susskind and L. Bacow

A broad program of research about techniques for mediating environmental disputes. Case studies of negotiation techniques for environmental disputes are developed for use in training workshops and professional education.

Negotiated Rule Making

L. Susskind and J. McMahon

Analysis of current federal efforts to experiment with mediated rule making. The objective is to evaluate the advantages and disadvantages of mediated approaches to the development of federal rules and regulations and to evaluate current EPA, FTC and DOE demonstrations.

Expert Systems for Hazardous Waste Remedial Actions

D. H. Marks

Implementation of an expert system to help planners focus on the correct site clean-up strategy for existing hazardous waste sites under the Superfund program.

Environmental Impact Assessment Review

L. Susskind and T. Hill

Each issue of this quarterly includes: brief summaries of new analytic techniques and breakthroughs in environmental decision making; articles addressing some of the urgent problems in the field; editorials; announcements of organization activities; and book reviews. The *Review* is based in the Center for Technology, Policy and Industrial Development.

Policy Issues in Regulation of Toxic Substances

N. A. Ashford

Examination of a variety of strategic and policy issues in the testing and regulation of toxic substances, including the problems of small volume and new chemicals, maintenance of innovation, complex and variable chemical substances, and an early warning system for future chemical technology trends.

Societal Controls for Health and Safety Hazards: An Historical and Ethical Assessment

N.A. Ashford, W.C. Priest, and D. Hattis

Elucidation of the underlying values and ethical principles reflected in both current

Mutagenic Assay

W.G. Thilly, A.L. LaFleur, and A.G. Braun

A chemical and toxicological analysis of particulate and gas effluents from various combustion systems. The toxicologic analysis is based on mutation of bacteria and human cells.

Morphologic Evaluation of Effects of Respiratory Toxicants

A.E. Rogers, M. Conner, and M.O. Amdur

Exposure by inhalation to aerosolized amounts of metal oxides and sulfur dioxide that may be generated in the air by burning coal induces physiological, morphological, and biochemical abnormalities in the respiratory tract of guinea pigs. Sensitive methods to measure interstitial edema, inflammation, epithelial cell permeability, damage and turnover, and endothelial cell injury are used to demonstrate and quantify the effects of single and repeated exposures.

Toxicology of Inorganic Coal Combustion Aerosols

M.O. Amdur, J.F. Elliott, A.F. Sarofim, and J.F. McCarthy

A project examining the toxic effects of combustion aerosols alone and in combination with sulfur dioxide (SO₂). Methods include pulmonary function in guinea pigs, studies of deposition, clearance, and biological uptake, and studies of pulmonary pathology. Aerosols of both pure metal oxides and coal combustion are characterized as to chemical composition, size, shape and surface enrichment of trace metals.

health, safety, and environmental legislation, and in later administrative and judicial actions implementing that legislation. The four major tasks are: description of the background of historical forces underlying demands for increased control of health and safety risks; development of a conceptual framework to define the goals of and ethical principles underlying social hazard control systems; survey of the legislative history and subsequent implementation of hazard control laws; and assessment of coherence of control principles within and between different programs.

Development of Better Methods for Quantitative Health Risk Assessment

Dale Hattis

Research into (1) the use of pharmacokinetic models to improve carcinogenic risk assessment; and (2) the effect of human interindividual variability on population risk from toxic chemicals.

Interest Group Strategies and the Regulation of Health, Safety, and Environmental Risks

D. Metlay

Interest groups are deeply involved in regulatory agency proceedings with respect to the control of health, safety and environmental risks. This research is designed to show why some groups participate and others do not and, for those who do participate, how they choose and implement strategies designed to influence regulatory choice.

Consumer Product Fears

H. M. Sapolsky, S. Weiner, M. Segal, and L. Cummings

A study of the health and safety challenges to consumer products, focusing on the dynamics of issue development and the attempts to contain market effects.

Incineration conference

tackles confrontation issues

"Hazardous Waste Incineration: Confronting the Sources of Disagreement" was the title of a conference held at the MIT Faculty Club on June 13 and 14. The conference was sponsored by the Institute's Hazardous Substances Management Program, based in the Center for Technology, Policy and Industrial Development. The purpose of the meeting was to bring together people who disagree about the need for incinerators, their safety, and the fairness of decisions to explore options that will lead to action.

Dr. John Ehrenfeld, coordinator of the Hazardous Substances Management Program said that "The conference achieved our goal of beginning a dialogue among interests with a long history of confrontation and disagreement." In his opening remarks to the conference participants, Ehrenfeld also noted that "Answers to the waste management problem transcend technology. Answers must come from a consensus of all concerned parties."

Participants in the invitational conference included 21 leaders from environmental groups, government, industry, and professional associations. Among those attending were Diane Walker, Chair of the Sierra Club's Hazardous Materials Committee; Ronald Kagal, Environmental Director for Dow Chemical Company; and Sonya Stelmack, responsible for coordinating EPA's program for permitting incinerators. In order to achieve balance, conference organizers invited an equal number of representatives from each of the key interest groups.

According to conference participants, a primary reason for attending was to gain a better understanding of the positions of other groups. Several people indicated that, because conflicts over incineration are highly politicized, parties lose the ability to see an adversary's point of view. Others noted that they would like to come to a common understanding of where incineration fits in to the waste management spectrum.

The conference began with a discussion of a paper prepared by the MIT Hazardous Substance Program entitled "Analysis of Advocacy Positions" in which the positions of the key groups active in the incineration debate are identified. Points of disagreement include the need for incineration, the safety of incinerators, the usefulness of risk assessment, the responsibility and obligations of private industry, and the appropriate level of intervention of nonprofessionals in decision-making.

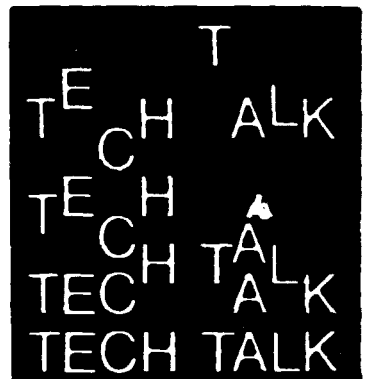
Conference facilitator Lawrence Susskind, Professor in the Department of Urban Studies and Planning, then asked participants to suggest ideas for dealing with conflict over incineration more effectively, given their positions. Suggestions fell into five areas:

1. Public participation and education. Government, industry, and citizens must share responsibility for solving waste management problems. Industry should engage the public early in its decision-making process.
2. Protocols for monitoring and enforcement. Standards should focus on total emissions in all media (air, water, ash residue). As technology advances, standards should become more stringent.
3. Framework for analyzing risks, benefits, and costs. Risk assessment should take social costs and benefits into account and not result in a shift of pollutants from land to air, or air to water.
4. Testing and certification of facility operators. The goal for testing and certification should be to achieve the desired level of service and safety while enhancing the credibility of the proposed facility's operation.
5. Connection of incineration to other options. The public will not accept incineration over other options. The public will not accept incineration facilities until industry and government commit themselves to waste reduction and recycling.

In the coming months conference organizers will work with participants to flesh out specific programs for action in these areas. The conference was part of the ongoing effort of the Hazardous Substances Management Program to couple new technology with new models that shape the way we see the world and take individual and collective action.

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SOLAR DESALINATION

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ABSTRACT

During the last decade solar desalination has been a subject of considerable interest, especially at a research and development level. This paper examines various systems using solar and wind power. Industrial development of these processes is now limited by two major factors: high investment costs and uncertain reliability.

INTRODUCTION

Fresh water availability is vital for the socioeconomic development of any region. Water is not only indispensable to life itself, but also affects all aspects of development including livestock breeding, crop irrigation and industrial development. In many arid or semiarid regions, water is rare and the demand is increasing in response to a growing population and to a rising standard of living.

Desalination of seawater or brackish water may provide a solution to this crucial problem in certain cases. Large scale plants capable of furnishing several hundred thousand cubic meters of water per day are already operating, primarily in the Middle East: Saudi Arabia, Kuwait, Qatar, Abu Dhabi, etc. (Figure 1).

Most of these plants use distillation processes, especially flash distillation (Table 1), which are energy-intensive and require large amounts of fuel oil or gas. For a large capacity plant operating at a high load factor, energy consumption represents 40% to 50% of the total cost per cubic meter of water produced. With rising energy prices, many countries are now interested in renewable energy forms for desalination.

This paper reviews the current status of desalination by renewable energy sources, and attempts to determine the reasons that currently limit the industrial development of such techniques.

DIRECT SOLAR DISTILLATION

The use of solar energy to distill water is not a recent idea: in the 3rd century B.C. Greek sailors were already using ingenious "seawater stills".

In 1608 J.E. della Porta illustrated the principle in his book "De Distillationibus". The glazed distillation unit (Figure 2) is thus the simplest and most ancient desalination process. The water vapor produced condenses on the glass panes, which are used as a cold source. Unfortunately, the production capacity of this method does not exceed 4-5 liters per day per square meter of water surface, and vast glazed areas quickly become necessary.

Recent units of this type include a 1860 m² distillation plant at Awaria, India, built in 1976 by the Central Salt and Marine Chemicals Research Institute, with a capacity of about 5 m³/day (1), and a 600 m² facility commissioned in June 1974 on the island of Ryobu-To in Japan, with a daily production capacity of about 2 m³.

The specific cost of a conventional glazed distillation unit is difficult to estimate, as the price may vary significantly depending on whether the materials used (glass or plastic) are imported or manufactured locally, whether the work is done by costly European or relatively inexpensive local labor, and whether the facility is built by a private company with a profit motive or by a nonprofit government agency. It is thus illusory to indicate precise cost estimates other than on a case by case basis.

According to a recent estimate, the cost of a glazed distillation plant ranges from FF 250 to FF 1000 per square meter, depending on labor costs (2). Assuming a 15-year service life, which is probably optimistic, a specific output of 4 liters per m^2 per day (i.e. about $1.2 m^3/m^2/year$), and an interest rate of 10%, the cost per cubic meter of fresh water ranges from FF 250 to FF 1000, considering only the financing costs. It is assumed that operation and maintenance will be ensured by gratuitous family labor (Table 2).

Contrary to a widespread belief, the cost of desalination by a solar distillation unit is high with regard to the relatively modest performance of this process.

Numerous improved versions of the conventional solar distillation unit have been proposed:

• Inclined Cascade Type Solar Distillation Unit

This unit has two advantages: the water layer is very thin, and the orientation of the collector relative to the incident solar radiation improves performance. A unit of this type (Figure 3) is sold by the French company SOLEFIL in Perpignan.

• Spherical Solar Distillation Unit

This design (Figure 4) was developed by Professor Menguy at the University of Lyon, and comprises a Plexiglas sphere containing a vessel filled with salt water. Water vapor condenses on the upper hemisphere and the condensate is collected at the bottom of the lower hemisphere.

• Capillary Film Solar Distillation Unit

In this design, developed by Professor Legoff at the Chemical Engineering Science laboratory in Nancy with the collaboration of Professor Baches at the University of Algiers, brackish water flows slowly along a thin fabric layer that lines the upper face of the collector. The vapor condenses on the cold wall located immediately below (Figure 5).

This unit should produce 10 to 15 liters of water per square meter per day under insolation conditions providing 2.5-3 $l/m^2/day$ with a conventional solar distillation unit.

CONVENTIONAL AND RENEWABLE ENERGY SOURCES FOR DESALINATION

Glazed distillers are the only truly "integrated" solar distillation systems. All the other techniques now being developed use renewable energy sources with conventional desalination processes: distillation, reverse osmosis or electrodialysis.

However, it is not sufficient to replace a conventional (fuel oil, gas, electricity) energy source by a renewable energy source to obtain a solar desalination facility. Two essential characteristics of renewable energies must be taken into account: their high cost and intermittent availability.

The high cost of renewable energies is due in particular to their generally low catchment yields and often hostile climatic conditions (saline marine air, tropical temperatures, hurricanes, etc.). High energy cost requires the use of very high-performance desalination processes. Table 3 indicates the order of magnitude of energy consumption for various desalination processes. As the actual energy consumption is closely related to the operating conditions, notably the transfer gradient (reverse osmosis pressure, distillation temperature difference, electro dialysis potential difference), two values are listed for each processes: the underlined value represents the current state of the art.

Solar energy is a discontinuous source, not only because of the regular day/night cycle but also because of less predictable climatic conditions. Some means must be found to adapt this intermittent energy source to continuous fresh water production: the high cost of desalination plants makes it economically indispensable to operate them on a 24 hour a day basis. Limited storage capacity is required for the day/night cycle, while climatic conditions require greater storage capacity to maintain nominal production regardless of the weather.

Solar energy applied to desalination may be schematically represented as follows:



The problem is thus to optimize the system from an economic standpoint.

DISTILLATION PROCESSES AND SOLAR ENERGY

At first view the distillation processes appear more suitable for use with solar energy. A distillation plant requires primarily thermal energy to heat the seawater (from 100 to 40 Mcal/m³ of fresh water depending on the plant efficiency). Moreover, this thermal energy must be supplied at relatively low temperatures (generally below 100-110°C) to avoid scale problems, especially with calcium carbonate. Under these conditions the thermal energy requirements of a distillation facility can be met by flat solar collectors if the plant operates at low temperatures (60-70°C) or by concentration collectors if the unit operates at higher temperatures (90-110°C).

Either multistage or multiple effect distillation processes may be used. The multistage technique is the most widely used process in the world at the present time, but is not the most suitable for use with solar energy. A high-performance multistage facility would require at least 30 or 40 stages implying very high manufacturing costs, especially for small scale units. Substantial energy is required to recirculate the seawater (4-5 kWh/m³), and the process is lacking in flexibility. Nevertheless, a 10 m³/day multistage unit powered by cylindrical-parabolic solar collectors has been installed in Kuwait by the Kuwait Institute for Scientific Research (3).

The multiple effect process, on the other hand, has a number of advantages and is better suited to solar energy. It allows flexible operation, has high production efficiency and features low mechanical energy consumption.

Several prototype plants have been built recently.

• **PYTHON** (a French acronym for Industrial Submerged Horizontal Tube Prototype) designed and built by the Heat Transfer Service of the Grenoble Nuclear Research Center 141, has been operating at the experimental station in Toulon since 1981. It implements a multiple effect process with the following specifications:

- Operating temperature	70°C
- Number of effects	12
- Production capacity	1 m ³ /h
- Thermal energy consumption	60 Mcal/m ³
- Mechanical energy consumption	1 kWh/m ³

The relatively low operating temperature (70°C) has several advantages, allowing standard flat solar collectors to be used and limiting scale and corrosion problems. In conjunction with an energy storage system (e.g. hot water) for continuous operation, the production capacity is about 25 m³/day. The specific production rating of this type of system is on the order of 30-40 liters/m²/day, compared with 3-5 liters/m²/day for a glazed distillation unit.

• Following this experimental work, a 50 m³/day sprayed-tube multiple effect plant will be built in 1986 in Guadeloupe by the French company Entropie.

• Finally, an 18-effect horizontal sprayed tube distillation unit was commissioned in Abu Dhabi in 1985 in cooperation with the Japanese. This 120 m³/day plant is supplied with energy by 1862 m² of solar collectors (5).

PHOTOVOLTAIC ENERGY AND DESALINATION

The current high cost and limited medium-term development prospects of photovoltaic energy production make it applicable only to desalination processes with very low energy requirements such as reverse osmosis or electrodialysis, and only for brackish water.

• Photovoltaic Energy and Electrodialysis

Electrodialysis consists in inducing salt migration under the effect of a direct current flow. Existing plants are generally supplied with rectified AC power. Photovoltaic cells supply DC power directly, and thus appear suitable for use with this type of desalination process. Moreover, flat solar collectors could be used to preheat the process water to about 45°C, as the performance of an electrodialysis system is temperature-dependent, increasing at the rate of about 2-3% per degree Celsius.

An experimental unit with a capacity of 1.25 m³/h from brackish water (4 g/l) is now being tested at Borj-Cedria in Tunisia (Figure 7).

• Photovoltaic Energy and Reverse Osmosis

Electric power is only necessary in a reverse osmosis unit to operate a high pressure pump. As a result, major developments are likely in which this process is coupled with photovoltaic energy. The power requirement is on the order of 1 to 3 kWh/m³ for brackish water and, assuming an energy recovery system is provided, about 5-8 kWh/m³ for seawater.

A 300 m³/day seawater desalination unit was commissioned in April 1981 at Jeddah by the American companies Moby-Tico and Water Services of America. Power is supplied to this plant only by photovoltaic cells with a peak rating of 8 kW 161.

A 50 m³/day brackish water desalination plant is scheduled to begin operation in 1986 at El Maarawin, Egypt.

WIND ENERGY AND DESALINATION

Many islands or coastal regions remain undeveloped for lack of an adequate fresh water supply. These regions are often swept by high winds, capable of operating a desalination unit using constantly renewed wind energy. Here again reverse osmosis seems to be the most suitable process.

A number of experimental units have been tested in recent years.

- On Planier Island, near Marseille, an AEROWATT 4100 FF7 wind-driven generator rated at 4 kW for a wind velocity of 7 m/sec has been used by the Cadarache Nuclear Research Center to operate a reverse osmosis seawater desalination plant with low energy consumption, producing about 5-6 m³ of fresh water per day (Figure 8) 171.

- The German company BISS has tested a 10 m³/day reverse osmosis unit on a North Sea island, powered by a three-blade wind generator manufactured by Allgäuer-Hütter, rated at 1 kW for a wind velocity of 9 m/sec.

THE EXPERIMENTAL RENEWABLE ENERGY DESALINATION STATION AT BORJ-CEDRIA (TUNISIA)

In each of Tunisia, especially in the South, fresh water constitutes a problem of quantity (i.e. totally unavailable) or quality (heavily brackish water) despite a major government-sponsored program of drilling, water supply, tank transports, etc.).

Desalination projects were considered and several plants using conventional energy sources (fuel oil or electricity) were built including a distillation plants for industrial water supply in the Gabès region and a 4000 m³/day reverse osmosis plant recently commissioned on the island of Kerkennah.

However, desalination has not been implemented on a wider scale for various reasons, notably the high cost of desalinated water due in large part to the cost of energy, and the lack of adequate skilled labor and spare parts.

Under these conditions the Tunisian Ministry of Higher Education and Scientific Research decided in 1980 to undertake a research and development program on desalination by renewable energy forms in collaboration with France. The project is sited at Borj-Cedria, about 25 km south of Tunis: an experimental station was built and now includes the following facilities (Figure 9): several prototype glazed distillation units; a reverse osmosis seawater desalination unit capable of producing 0.25 m³ of fresh water per hour; and an electrodialysis unit with a production capacity of about 1.25 m³/h from brackish water with a salt content of 4 g/l.

The energy required to operate these systems is provided from a variety of sources: solar radiation for the glazed distillation units; a 1 kW wind generators for the pumping station and a 4 kW wind generator for desalination purposes (both ratings are effective for wind velocities of 7 m/sec or higher); a 4 kW peak rated photovoltaic generator; and 120 V storage batteries with a 500 A-h capacity.

The experimental station was officially inaugurated by President Bourguiba on May 29, 1984.

SOLAR DESALINATION: RANGE OF APPLICATIONS AND CHOICE OF TECHNIQUES

At the present time it would be unrealistic to consider building high capacity desalination facilities (e.g. 10 000 m³/day) operating on solar or wind energy for two major reasons: the investment costs are too high and the reliability of such systems has not been demonstrated.

On a smaller scale, however, fresh water production from brackish water or seawater may be considered using solar and/or wind energy (Figure 10). If the fresh water requirement does not exceed a few cubic meters per day, direct solar desalination in a glazed distillation unit is an attractive solution especially when skilled labor is unavailable. Seawater could be pumped into the unit by wind energy. The drawbacks of this solution are the large surface area required and the lack of a scale effect for larger units.

For higher fresh water needs (10-100 m³/day) it is preferable to couple conventional low-energy desalination processes with solar or wind power. It is very difficult to estimate the cost of such systems, however, as only prototype units are now in operation and their operating costs are unknown. In any case, the cost per cubic meter of fresh water produced in this low production range remains high, and a major research effort must be undertaken in order to provide a good quality water supply at reasonable cost to the populations of arid and semi-arid regions.

CONCLUSIONS

Solar desalination has received increasing interest since 1975:

- the PYTHON project (multiple effect distillation with flat solar collectors);
- the solar distillation unit at Abu Dhabi (120 m³/day with 1862 m² of solar collectors);
- the Borg-Cedria project in Tunisia;
- reverse osmosis units powered either by wind generators or photovoltaic cells.

In each case, these have been demonstration or research and development projects. Further development of these techniques will be possible only when two obstacles are overcome: one is a technical problem, the other is economic.

• Technical Problem

The desalination units must be reliable despite extremely severe operating conditions: very high temperatures (50°C in the shade), a complete absence of technical support, etc.

At first view this would seem to be an argument in favor of simple devices such as solar distillation units. However it may be expected that more complex systems such as multiple-effect units coupled with solar collectors, or reverse osmosis units powered by wind generators or photocells will reach acceptable reliability in the near future. Television sets and refrigerators are now used with no problems in the most remote regions, for example, but this degree of reliability was not achieved overnight.

• Economic Problem

The investment costs for solar desalination are currently too high. Given the high cost of renewable energy sources (investment costs once again), it is indispensable to use them with high performance (i.e. low energy-consuming desalination systems which are inevitably more expensive).

In many cases, however, the problem is not the absence of fresh water but a lack of money, and the high interest rates in recent years do not encourage the development of new techniques.

In other words, it may be possible to demonstrate that at the present oil prices solar desalination is capable of producing fresh water at a competitive price over a 15 or 20-year period. Unfortunately, the customer can not afford the investment.

It can only be hoped that ongoing research with close cooperation between the producing countries and the utilizing countries will be able to solve both problems and develop reliable solar desalination units at acceptable cost.

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Table 1: Installed World Desalination Capacity as of 1/1/1984

TYPE OF PROCESS		INSTALLED CAPACITY (m ³ /day)	%
Distillation Processes	Flash	5 980 000	-64
	Miscellaneous	620 000	-6
	Total Distillation	6 600 000	-70
Membrane Processes	Reverse osmosis • seawater	140 000	1.5
	Reverse osmosis • brackish water	2 200 000	25.5
	Electrodialysis	460 000	5
Total membranes		2 800 000	-30
OVERALL TOTAL		9 400 000	100

Table 2: Desalination Costs for Solar Still

Average production: 4 liters/m²/day, i.e. 1.2 m³/m²/year
 Financing: 15 years at 10% (annuity = 13.1%)

PRODUCTION CAPACITY (AREA)	UNIT COST	INVESTMENT COST (French Francs)	FRESH WATER COST (FF/m ³)
1 m ³ /day (250 m ²)	Distillers @ FF 250/m ²	62 500	27
	Distillers @ FF 500/m ²	125 500	54
	Distillers @ FF 1000/m ²	250 500	108
10 m ³ /day (2500 m ²)	Distillers @ FF 250/m ²	625 000	27
	Distillers @ FF 500/m ²	1 250 000	54
	Distillers @ FF 1000/m ²	2 500 000	108
50 m ³ /day (12500 m ²)	Distillers @ FF 250/m ²	3 125 000	27
	Distillers @ FF 500/m ²	6 250 000	54
	Distillers @ FF 1000/m ²	12 500 000	108

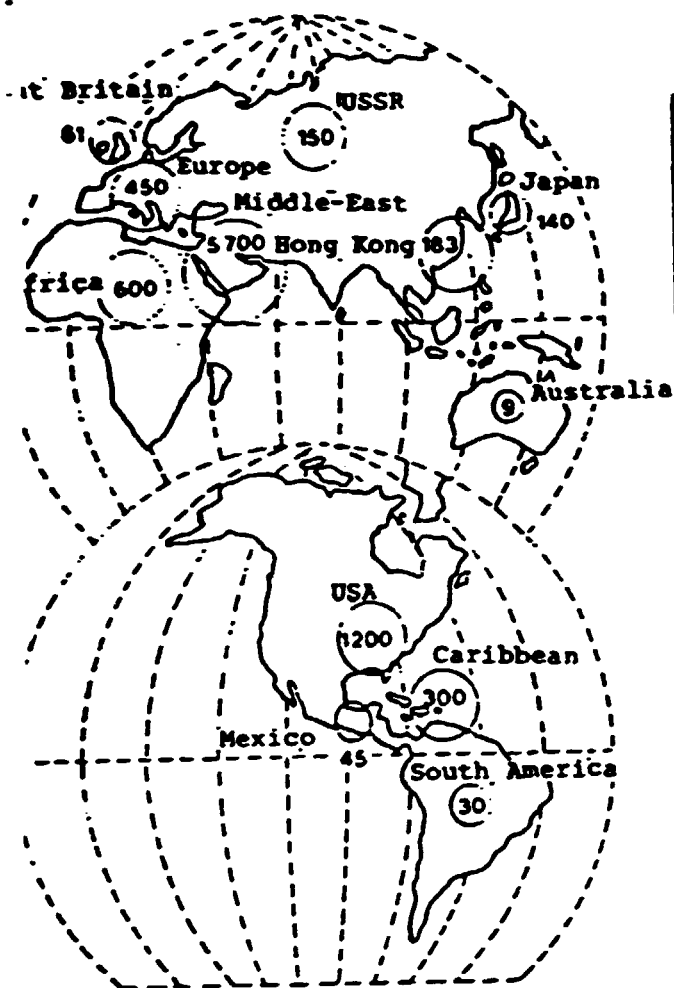
Table 3: Comparative Energy Requirements of Various Desalination Processes
Assuming the Primary Energy Source is Fuel Oil
(underlined values represent current state of the art)

DESALINATION PROCESS		Required energy $l/m^3 + kWh/m^3$	Amount fuel kg/m^3	
			Sing. purp.	Doub. Purp.
DISTILL. PROC.	<u>MULTIFLASH Ratio 8</u>	<u>70 + 3</u>	<u>8,45</u>	<u>3,5</u>
	MULTIFLASH Ratio 14	40 + 5	5,65	2,8
	<u>MULTIP. EFFECTS (7)</u>	<u>90 + 2</u>	<u>10,4</u>	<u>4</u>
	MULTIP. EFFECTS (12)	60 + 3	6,25	2,7
	<u>Steam compr(1) $\Delta t = 5^\circ C$</u>	<u>11 + 16</u>	<u>4</u>	<u>4</u>
	Steam compr(1) $\Delta t = 3^\circ C$	0 + 12	4	4
MEMBRANE PROC.	<u>RO seawater, no recov. (60 bar)</u>	<u>0 + 12</u>	<u>3</u>	<u>3</u>
	RO seawater + recov. (60 bar)	0 + 8	2	2
	<u>RO brack. 2.5g/l water (40 bar)</u>	<u>0 + 3</u>	<u>0,75</u>	<u>0,75</u>
	ED seawater 1.2 volt/cell	0 + 30	7,50	7,50
	<u>ED brack. 2.5g/l water 1.2 volt/cell</u>	<u>0 + 3</u>	<u>0,75</u>	<u>0,75</u>

(1) Single effect

RO Reverse osmosis

ED Electrodiagnosis



COUNTRY	Daily Production in m ³	%
MIDDLE EAST	5 700 000	61
USA	1 200 000	13
AFRICA	600 000	6
EUROPE	450 000	5
CARIBBEAN	300 000	3
HONG KONG	183 000	2
USSR	150 000	2
JAPAN	140 000	2
GREAT BRITAIN	61 000	1
MEXICO	45 000	1
SOUTH AMERICA	30 000	1
AUSTRALIA	9 000	1
MISCELLANEOUS	532 000	4
TOTAL	9 400 000	100

Figure 1: Worldwide Distribution of Desalinated Water Production
 x 1000 m³/day as of January 1984

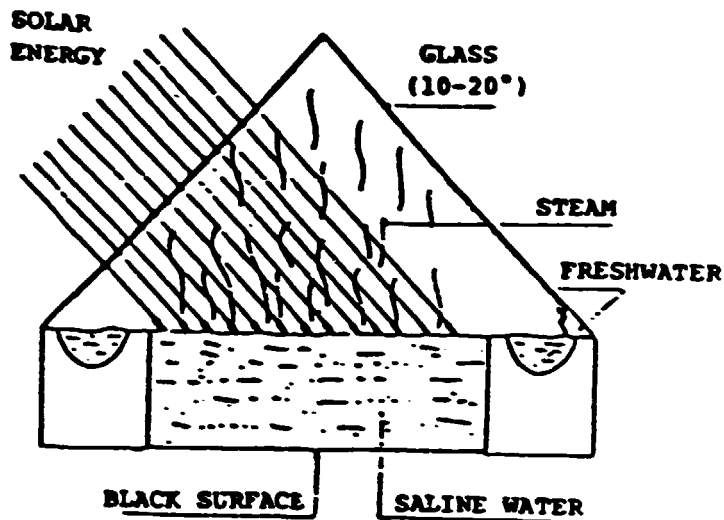


Figure 2: Schematic Representation of a Solar Still

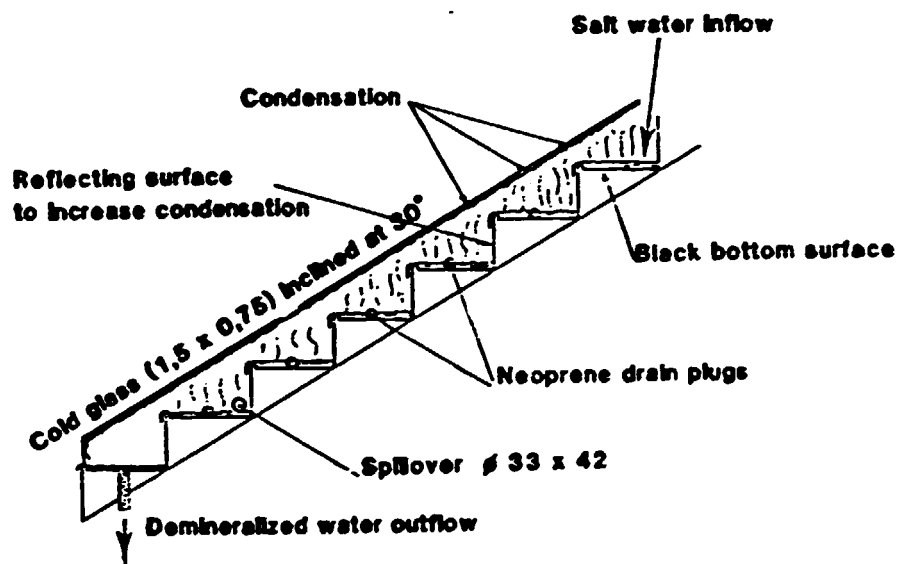


Figure 3: Cascade Distillation Unit

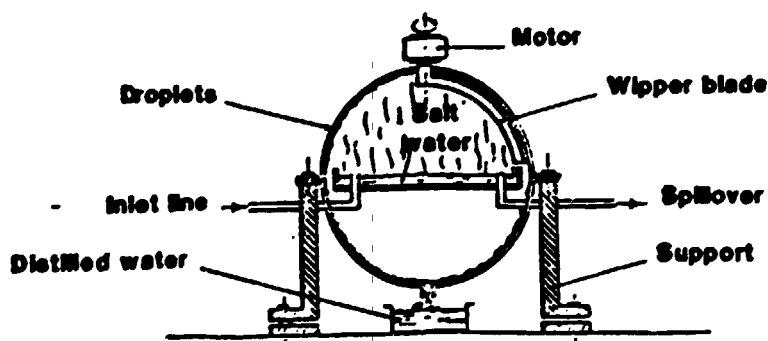


Figure 4: Spherical Distillation Unit

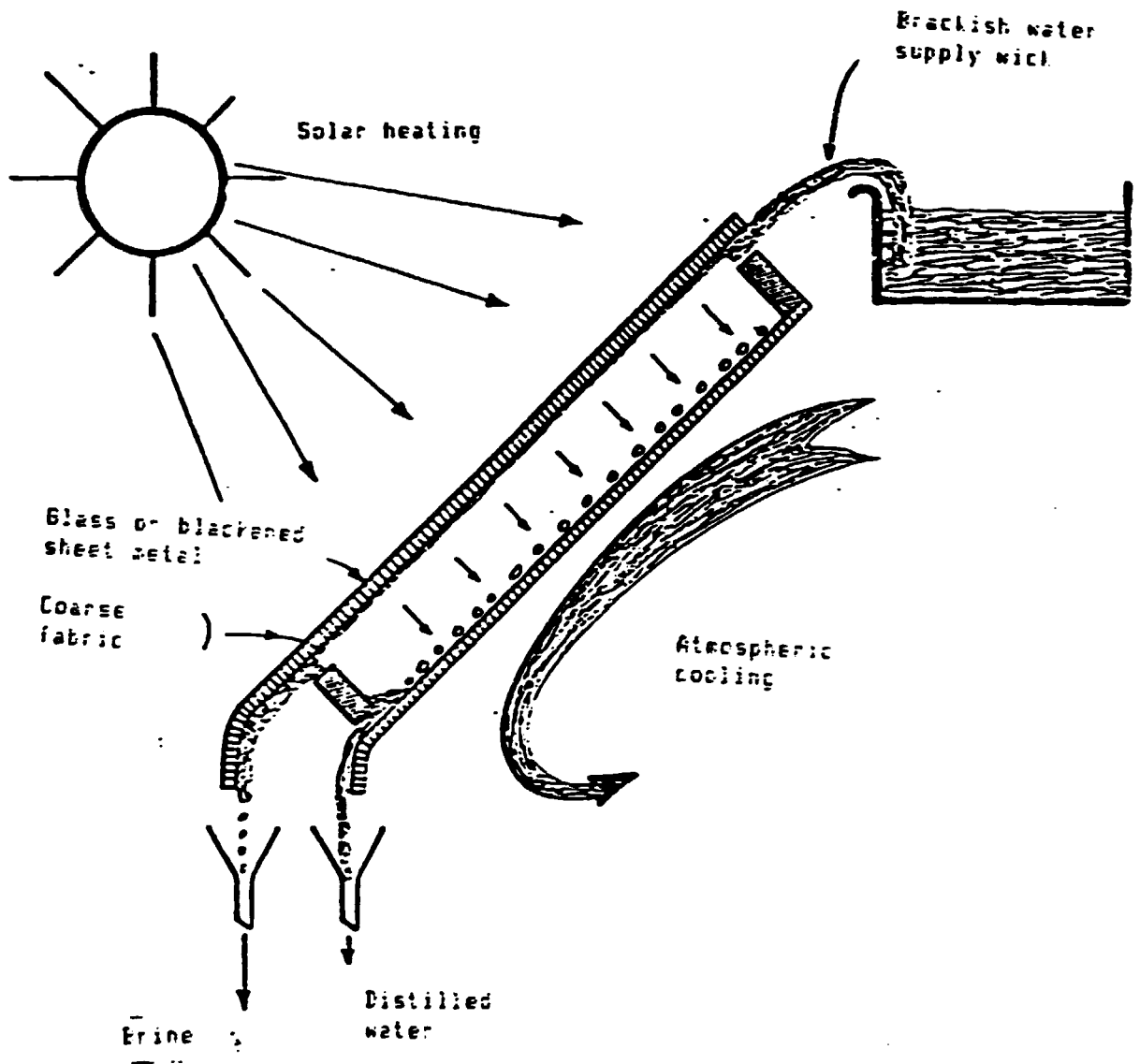


Figure 5: Capillary Film Distillation Unit
 Developed by Prof. Legoff
 (University of Nancy, France)

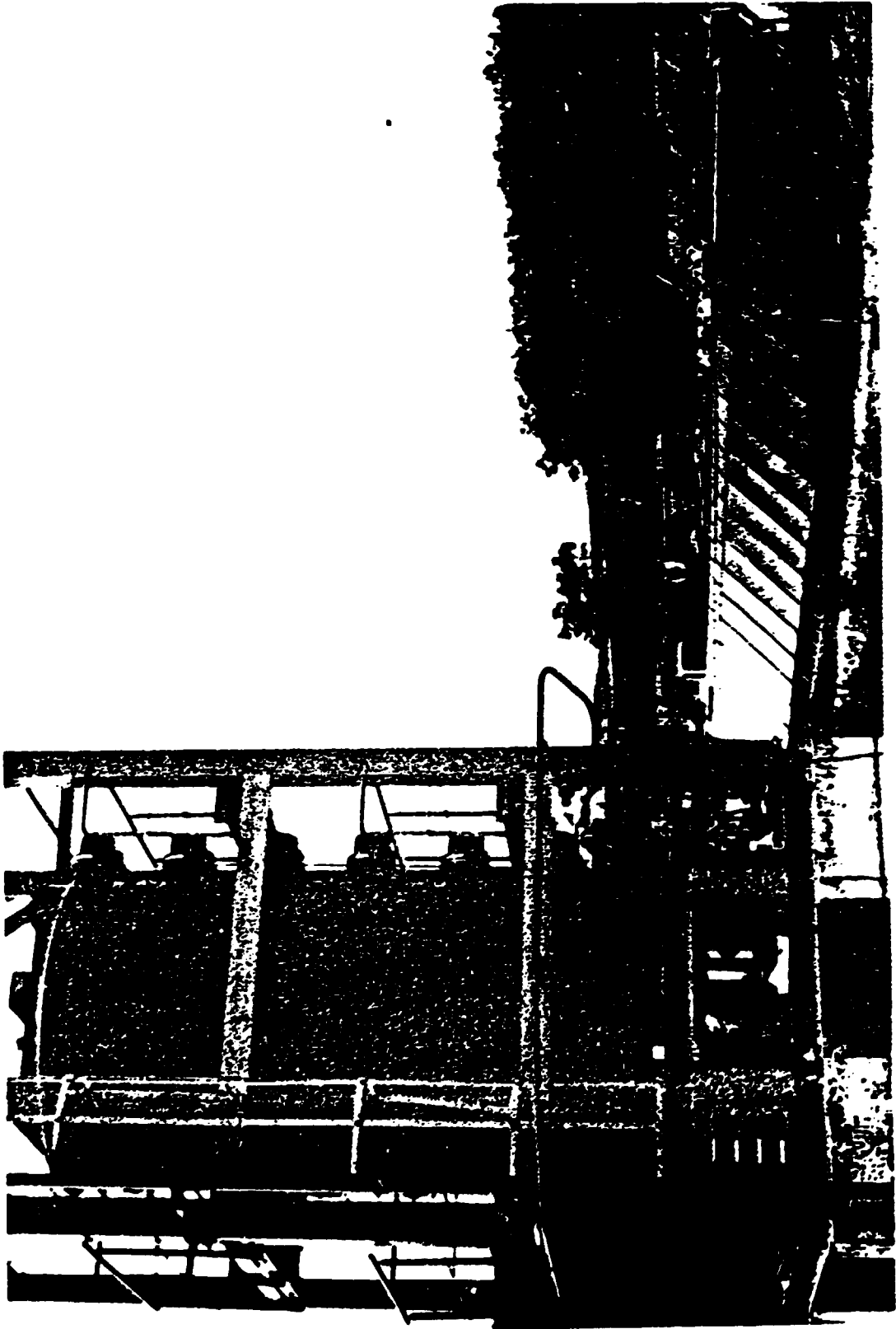


Figure 1. Schematic of the reactor system. The reactor is
coupled with the flat-plate collector
by the two heat transfer surfaces
of the collector tubes.

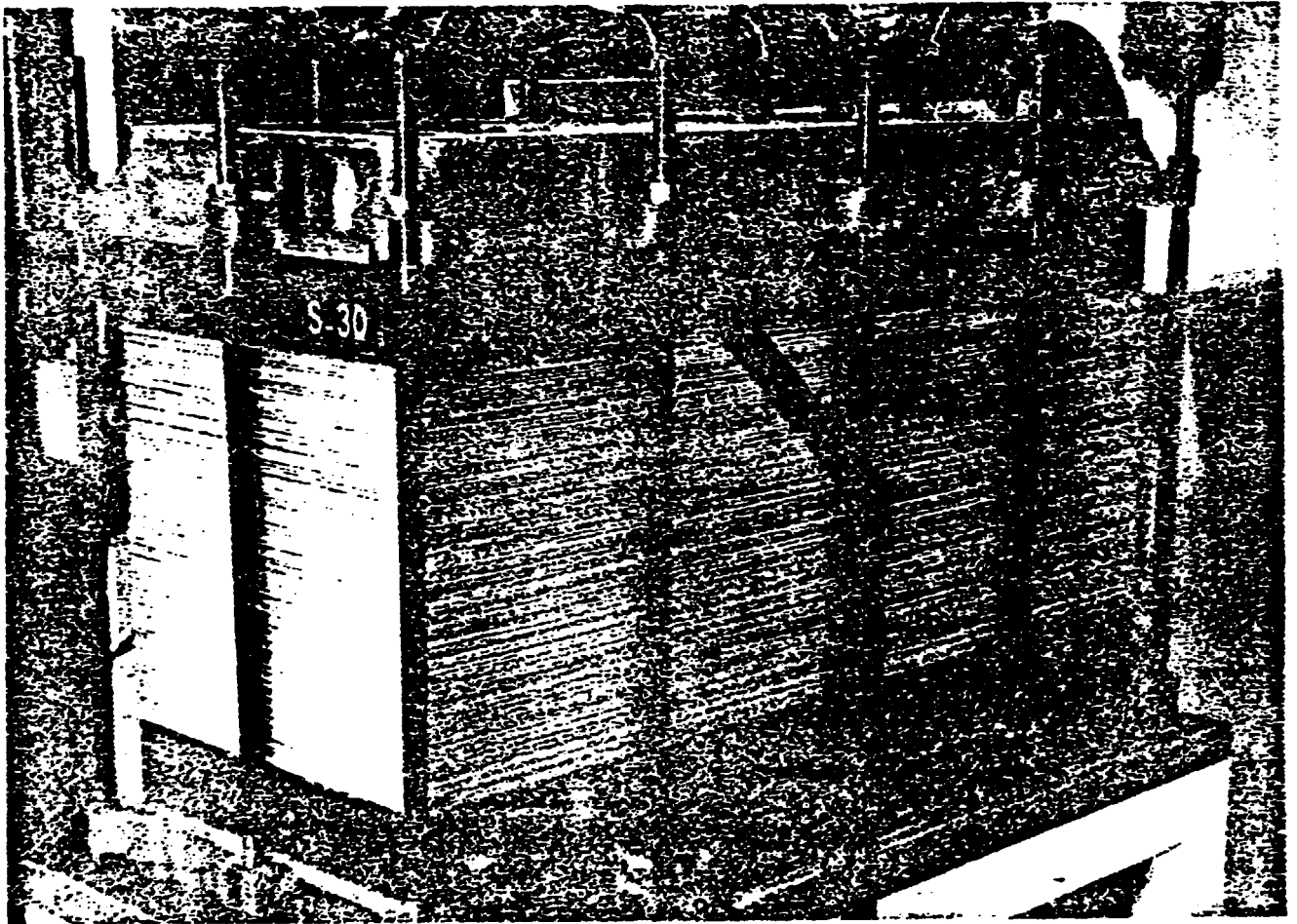


Figure 10. Electric power is used for water disinfection with
Powered by Photovoltaic Cells at Enny-Ceasse, Tunisia.
Production Capacity: 1.25 m³ per hour. Energy Water: 4 g/l.

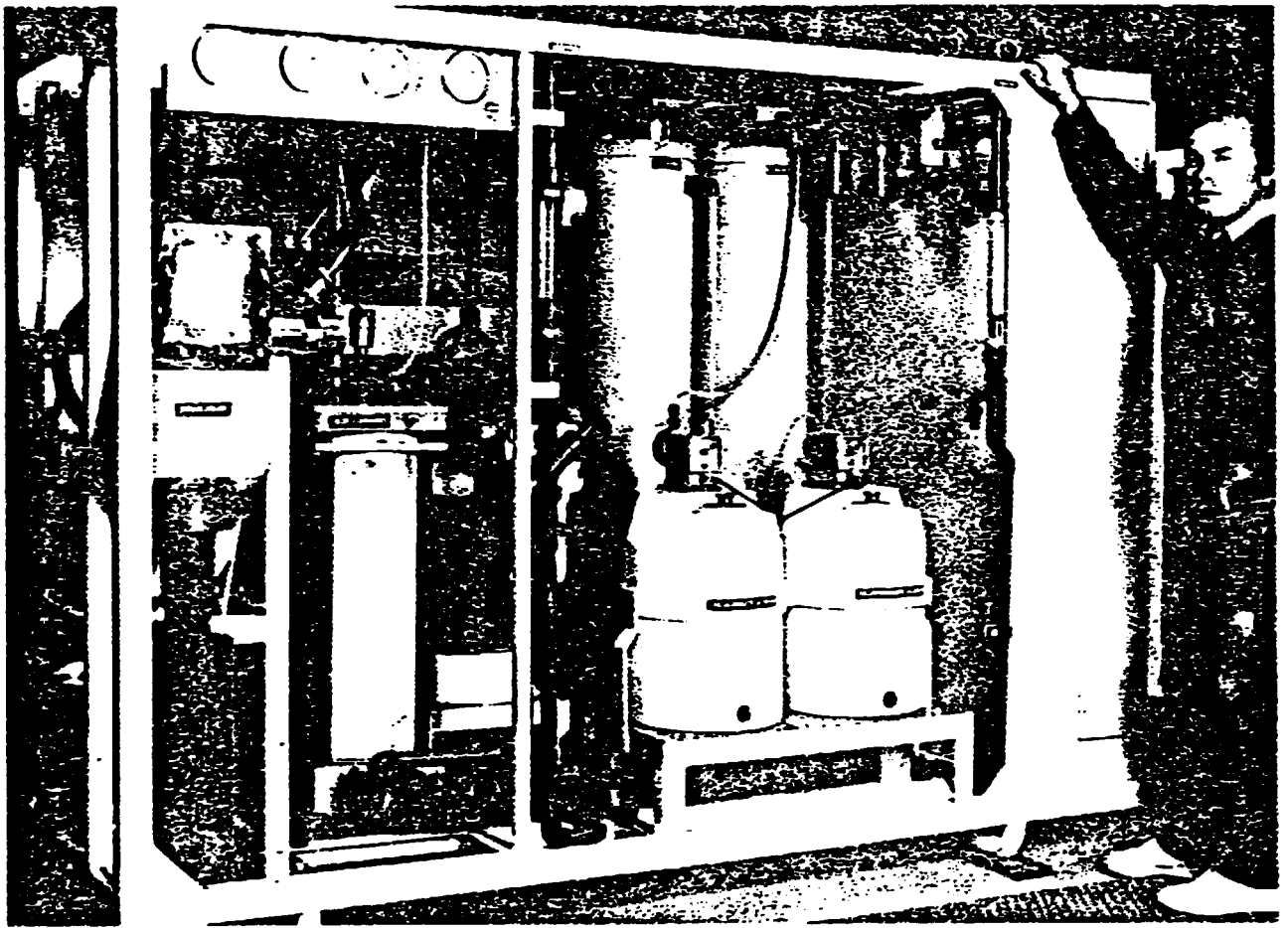


Figure B1: Low Energy-Consuming Reverse Osmosis Desalination Unit
Developed at the Tennessee Nuclear Research Center
for Coupling with a Wind-Driven Generator
Production Capacity: 0.5 gph



FIGURE 5: Experimental Proprietary Steel Installation Station
at Puy-Allouez, France.

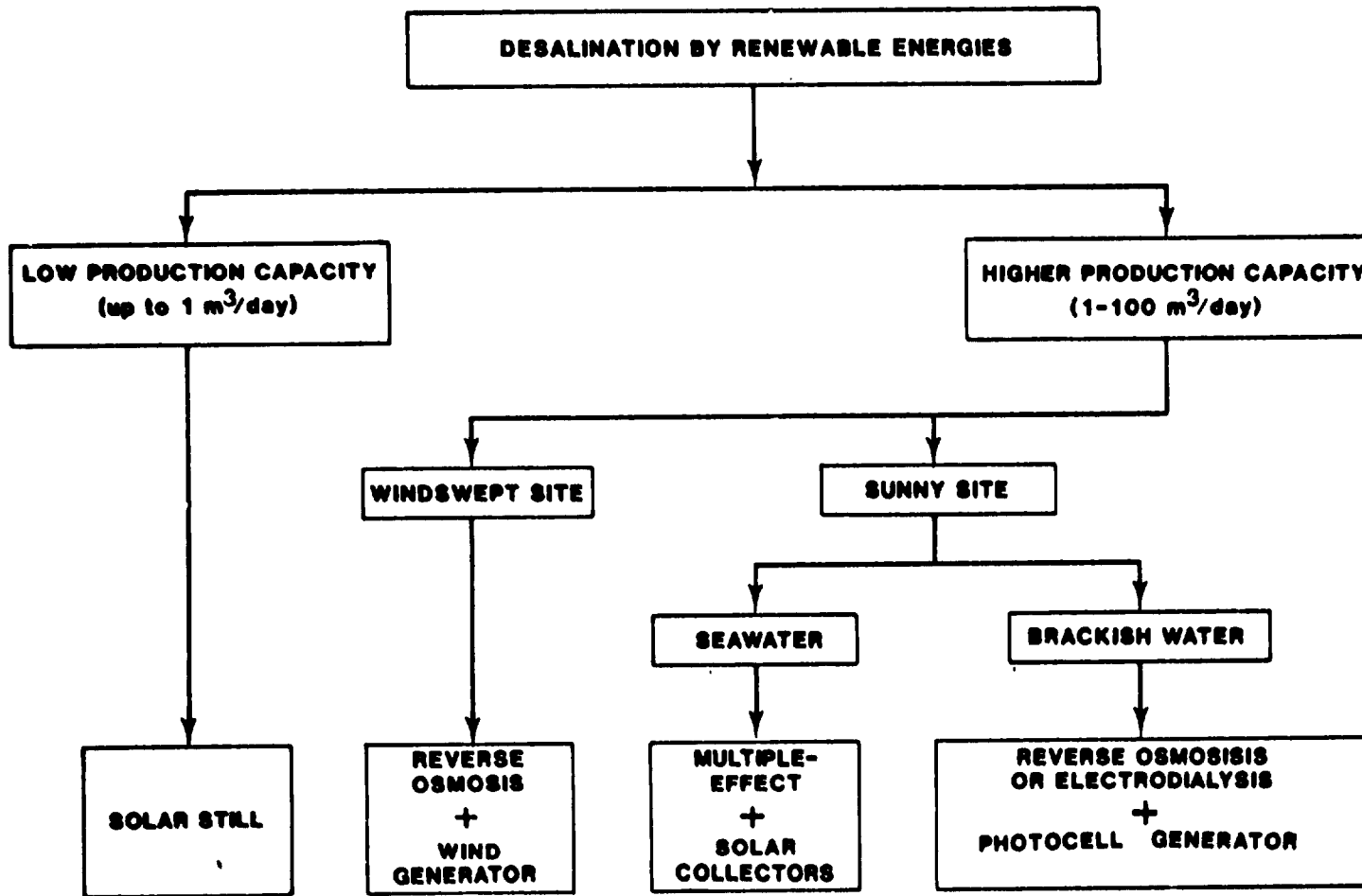


Figure 10: Solar Desalination:
Range of Applications and Choice of Techniques

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SEAWATER AND BRACKISH WATER DESALINATION

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Comparison of processes

The cost of desalinated water

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BY Mr. Alain MAUREL
Engineer, Research Manager
"Desalination Techniques"
Cadarache Center
Atomic Energy Commission

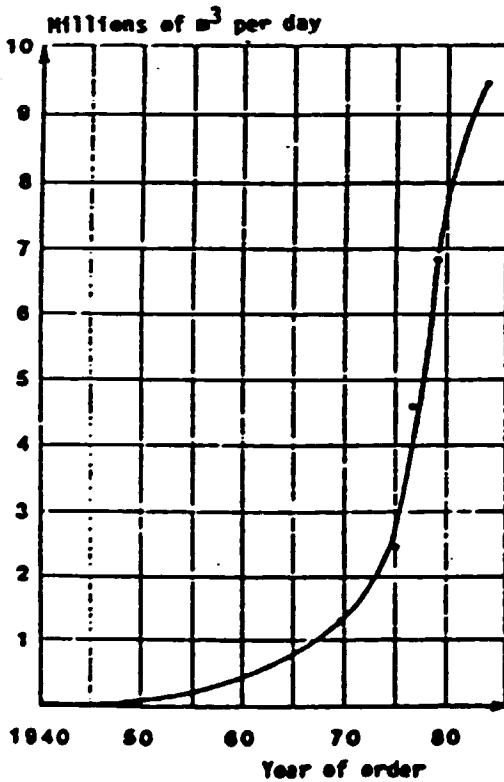
FEBRUARY 1986

INTRODUCTION

Water is tending to become a rare resource due to increasing consumption and more widespread pollution. Are we going to have a water crisis or should we be less pessimistic and simply take stock of our available resources and manage them? As the existing fresh water reserves are not limitless, even when purified and recycled, why not attempt to extract fresh water from seawater, which is in abundant supply? "Drinking seawater" is not a new idea as the Greek mariners were already well versed in the art of "boiling seawater" in the third century BC. Even Aristotle explained this natural phenomenon as follows: when seawater evaporates, it is transformed into freshwater and after condensation it no longer has a salty taste.

Today over 10 million cubic meters of freshwater are produced from seawater every day, as indicated in FIG. 1.

FIG.1 - ACCUMULATED WORLD CAPACITY OF DESALINATION PLANTS ON JANUARY 1 OF EACH YEAR.



Year	Accumulated world capacity in m ³ /day
1962	200 000
1963	250 000
1964	300 000
1965	325 000
1966	370 000
1967	570 000
1968	800 000
1969	915 000
1970	1 150 000
1971	1 210 000
1972	1 350 000
1973	1 600 000
1974	1 860 000
1975	2 100 000
1976	2 520 000
1977	3 155 000
1978	4 660 000
1979	5 200 000
1980	6 900 000
1981	7 450 000
1982	8 000 000
1983	8 700 000
1984	9 400 000

The aim of this report is to review the processes currently available and to give an idea of their cost. It should, however, be stressed that it is very difficult to analyze the cost with sufficient accuracy without treating each case individually and taking into account the local conditions.

a) Technical factors

. Salinity of the water being processed, i.e. seawater or brackish water. The salinity of seawater can even vary from 35 g/l in the Atlantic Ocean to 55 g/l in the Gulf of Arabia.

. Salinity of the processed water, i.e. drinking water or very pure water for industrial usage. Even when producing drinking water by reverse osmosis, one or two stages may be needed depending on customer requirements for a salinity not exceeding 500 mg/l or a level between 600 and 700 mg/l.

. The physical properties of the water, i.e. cloudiness, suspended matter, which can, especially for reverse osmosis, entail very complex preprocessing when the seawater is highly polluted or, on the contrary, no preprocessing when the water is very pure, e.g. submarines.

. The chemical properties when the water being processed is brackish, i.e. hardness, sulphate content.

. The workload, e.g. a facility designed to operate several weeks per year can have a relatively low output with a lower initial investment.

. The extent of the automation and control. In a small plant, installing equipment for measuring/recording the processed water pH, temperature and resistivity can lead to a substantially higher investment.

. Energy source available.

. Capacity of plant.

b) Economical factors

. Cost of energy, e.g. without cost on an offshore platform, quite low in the Middle East but extremely high at isolated sites. In some cases, such as the French Antilles or Arabia, the cost price can in no way be related to the price paid by the customer.

. Cost of chemicals, i.e. whether manufactured locally or subject to more or less long-distance shipping.

. Variations in exchange rates. This primarily affects the reverse osmosis modules, almost exclusively produced in the USA and for which accurate cost estimates cannot be given due to the fluctuations in the exchange rate of the dollar.

. Inflation existing in most countries in the West and in the Middle East countries.

. Financing terms, i.e. interest rates.

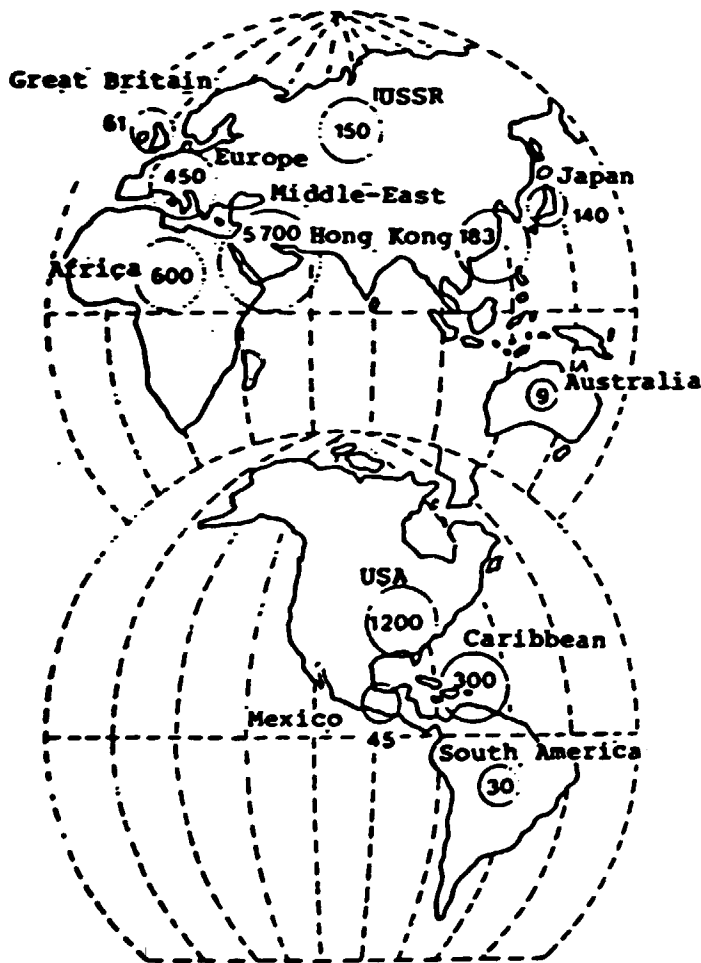
. Cost of manpower.

Even for individual cases, these costs are sometimes difficult to estimate. A case in point is the LP steam in a dual purpose plant (water + electricity), whose cost will depend on how the costs are divided out between the water and electricity.

In this type of context, the cost figures given in this report are only intended to give an order of magnitude for arbitrarily selected conditions, which allows the various processes to be compared.

As a large part of the market is located in the Gulf Region (Saudi Arabia, Union of Arab Emirates, Qatar, Iran, etc.), our estimates, especially for distillation, are valid for the Middle East context.

**WORLDWIDE DISTRIBUTION OF DESALINATION PLANT PRODUCTION
IN M³/DAY (JANUARY 1984)**



COUNTRY	Daily Production in m ³	%
MIDDLE EAST	5 700 000	61
USA	1 200 000	13
AFRICA	600 000	6
EUROPE	450 000	5
CARIBBEAN	300 000	3
HONG KONG	183 000	2
USSR	150 000	2
JAPAN	140 000	2
GREAT BRITAIN	61 000	1
MEXICO	45 000	1
SOUTH AMERICA	30 000	1
AUSTRALIA	9 000	1
MISCELLANEOUS	532 000	4
TOTAL	9 400 000	100

FIG. 2 - GEOGRAPHIC DISTRIBUTION OF DESALINATION PLANTS AS OF JAN 1, 1984

1 - DESALINATION PROCESSES

An author has recently counted 27 different desalination processes but, in fact, all the facilities in use are based on two main methods, i.e. evaporation processes and the more recent membrane separation processes. The world desalination production capacity as of January 1984 is given in Table 1 for the various processes. It should not be forgotten that the values for the membrane methods apply to brackish water, which has a salinity level (generally 1-10 g/l) below that of seawater. The mean ocean salinity is close to 35 g/l.

Type of process		Daily production in m ³	%
Distillation processes	Flash	5 980 000	~64
	Miscellaneous	620 000	~ 6
	Total for distillation	6 600 000	~70
Membrane processes	Reverse osmosis } . Seawater . Brackish water	140 000	1.5
		2 200 000	23.5
	Electrodialysis	460 000	5
	Total for membrane	2 800 000	~30
Overall total		9 400 000	100

TABLE 1 - WORLD DESALINATION PRODUCTION CAPACITY AS OF JAN 1,1984

1.1 - Distillation processes

1.1.1 - Single and multiple effect distillation

The first industrial freshwater distillation plants were introduced on ships at the same time as steam became available. Most of these were single effect boilers with a buried core where the seawater was heated in a sealed chamber by an array of tubes immersed in the seawater and carrying steam. The steam generated was condensed on another tube array carrying cold seawater in the upper part of the boiler (FIG. 3).

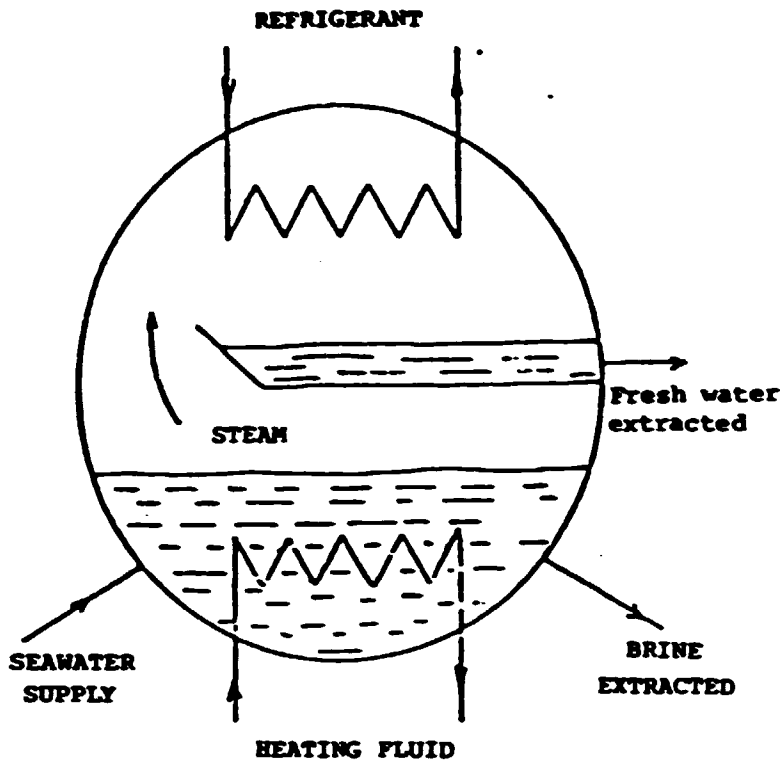


FIG. 3 - SINGLE EFFECT EVAPORATOR

This type of plant has a high power consumption of about 600 thermies ($600 \times 4.2 \times 10^6$ Joules) and is only feasible if low cost energy is available, as on ships where simplicity is of prime importance. It was therefore absolutely necessary to improve the specific consumption of this type of evaporator and this was achieved by using multiple effect distillation. The boiling temperature is known to vary with pressure and the condensation heat of the steam generated in the first chamber can thus be used to heat the heating array in a second chamber at a lower temperature and pressure, and so on (FIG. 4).

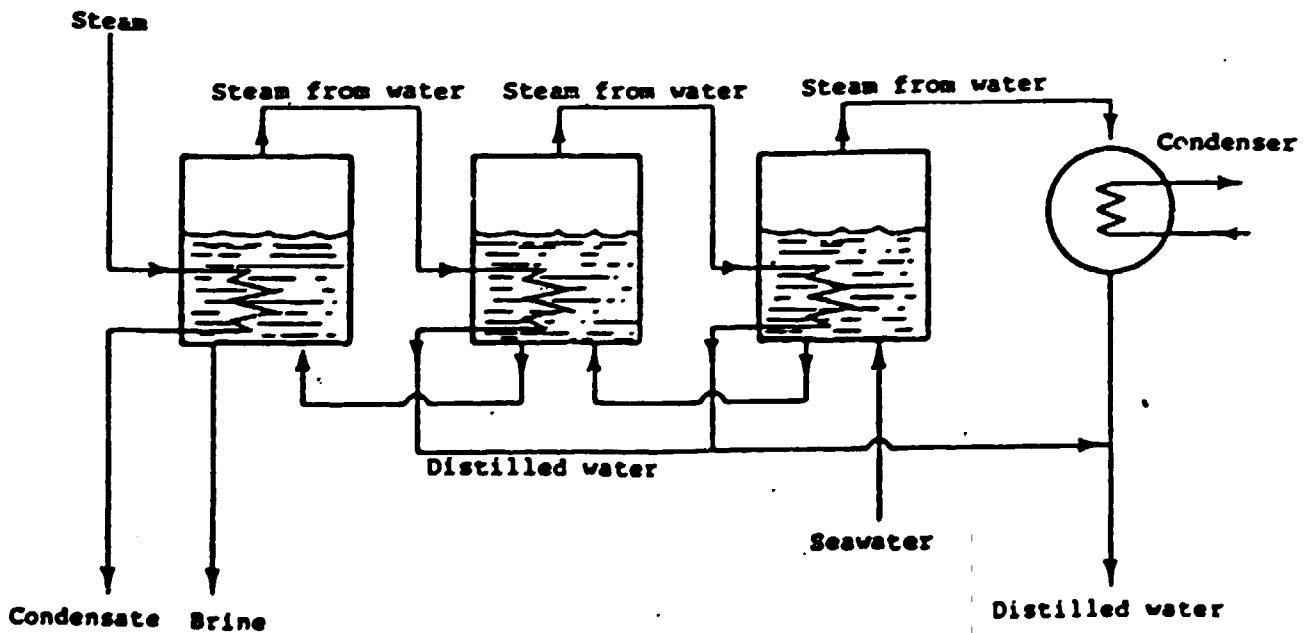


FIG. 4 - MULTIPLE EFFECT DISTILLATION

Only two of the several multiple effect evaporator variants will be discussed below: vertical long tube evaporators and sprayed horizontal tube multiple effect evaporators.

1) The vertical tube evaporators (VTE), which were patented by the French firm Kestner over 60 years ago, spray seawater from the top of multi-tube arrays in a thin stream down externally heated exchange tubes. The bottom of the unit collects the brine, which is fed to the upper half of the second unit, and the steam, which is used for heating the second effect. Although this method has the advantage of producing high heat transfer coefficients, it has not as yet succeeded in taking over the desalination market.

2) The horizontal tube multiple effect evaporators (HTME) are a more recent development and only became industrially available about ten years ago. They consist of horizontal tube arrays internally heated by steam and externally spray-cooled by seawater (FIG. 5).

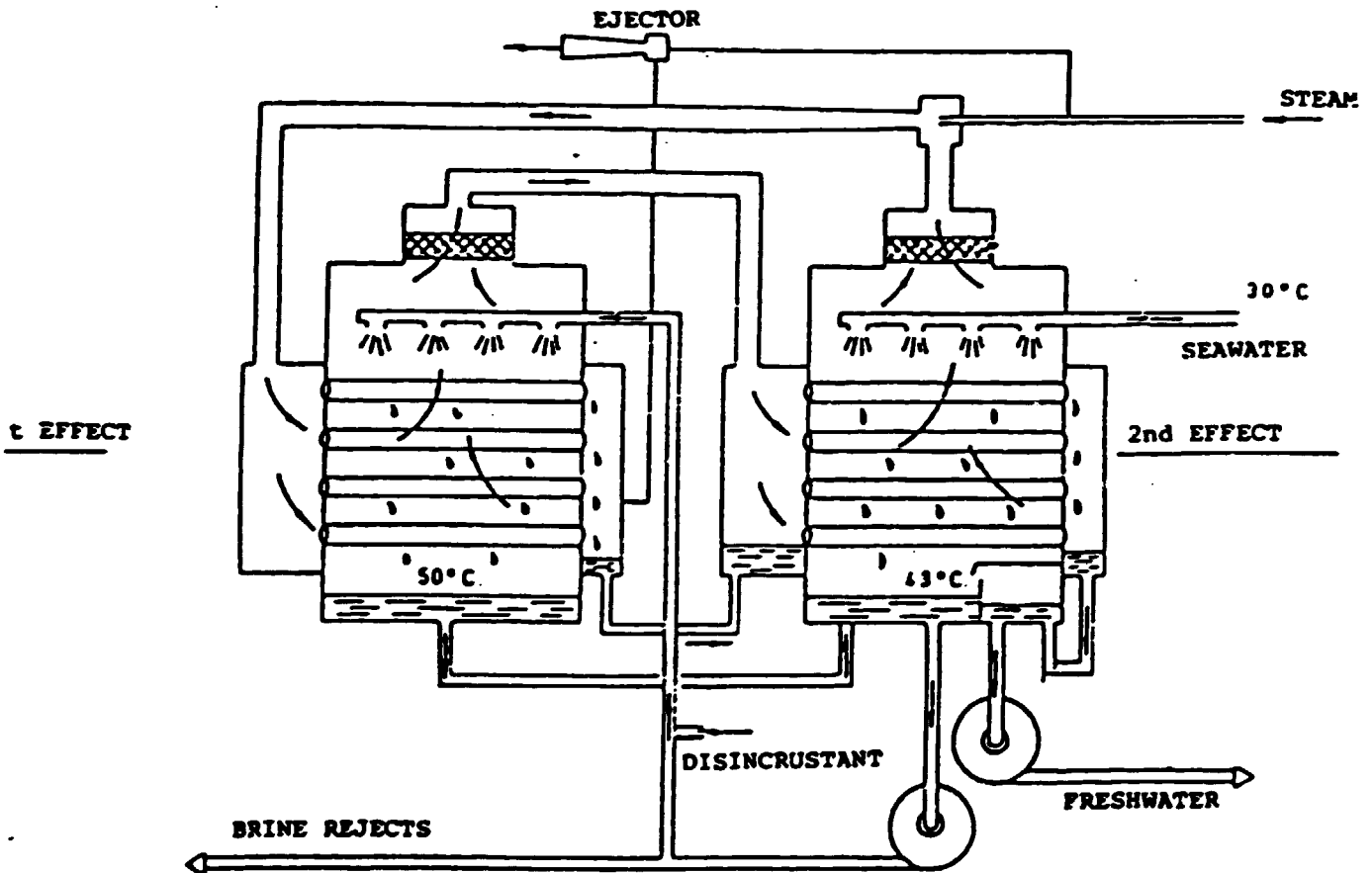


FIG. 5 - HORIZONTAL SPRAYED TUBE TWO EFFECT EVAPORATOR

1.1.2 - Successive expansion or flash processes

This process was mainly developed from 1950 on when scaling problems were encountered on the exchange surfaces in buried core evaporators.

In distillation by successive expansion, the seawater is kept pressurized throughout the heating period, thereby reducing the likelihood of scaling. It is then fed into a chamber at a pressure below the saturation pressure, which instantaneously causes vaporization through expansion. Part of the water evaporates, condenses out on the condenser tubes and is collected in containers (FIG. 6).

The first industrial plant using this process was built in Kuwait in 1957. Since then the use of the process has grown substantially, mainly in the Gulf countries, and today it alone accounts for 65% of the installed desalination capacity (Table 1).

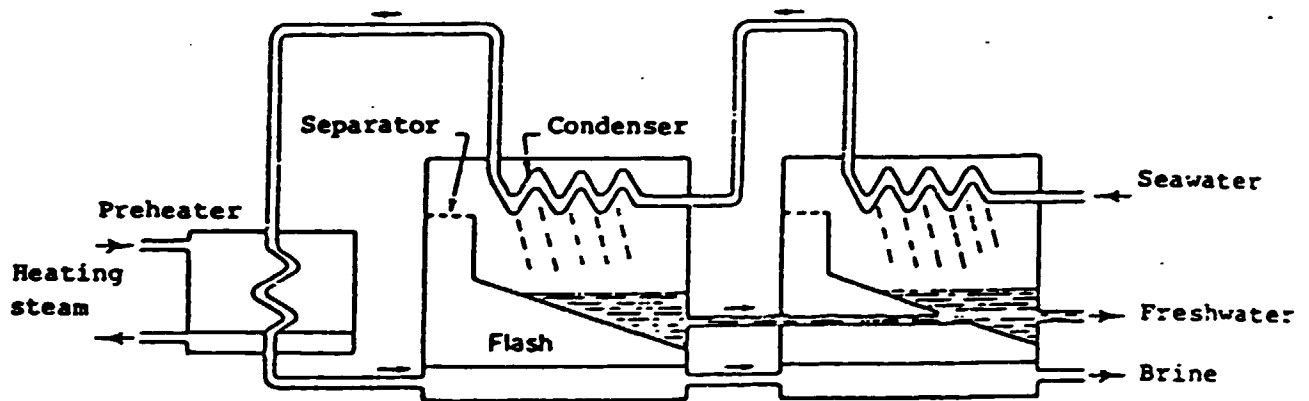


FIG. 6 - SUCCESSIVE EXPANSION OR FLASH DISTILLATION

Overall the multiple effect methods offer various advantages over the flash process, i.e.:

- . Very high operating flexibility with trouble-free production variations in a multiple effect facility running from 15 to 100% of the rated capacity. This is not economically viable with the flash process.
- . A much lower brine flowrate resulting in reduced energy requirements for pumping, i.e. 2-3 kWh/m³ for multiple effect and 4-5 kWh/m³ for flash.
- . Improved safety from the standpoint of the processed water salinity since a perforated tube in a multiple effect facility will only inject steam into the seawater.

However, for the moment the flash process is more widely used, especially since it has the advantage of higher unit yields, e.g. over 30,000 m³/day.

1.1.3 - Compression of steam (FIG. 7)

In this method, the water being desalinated is boiled in a thermally insulated chamber. The steam is compressed adiabatically, which increases its saturation temperature, and then directed through a tube array where it condenses and causes the seawater to boil.

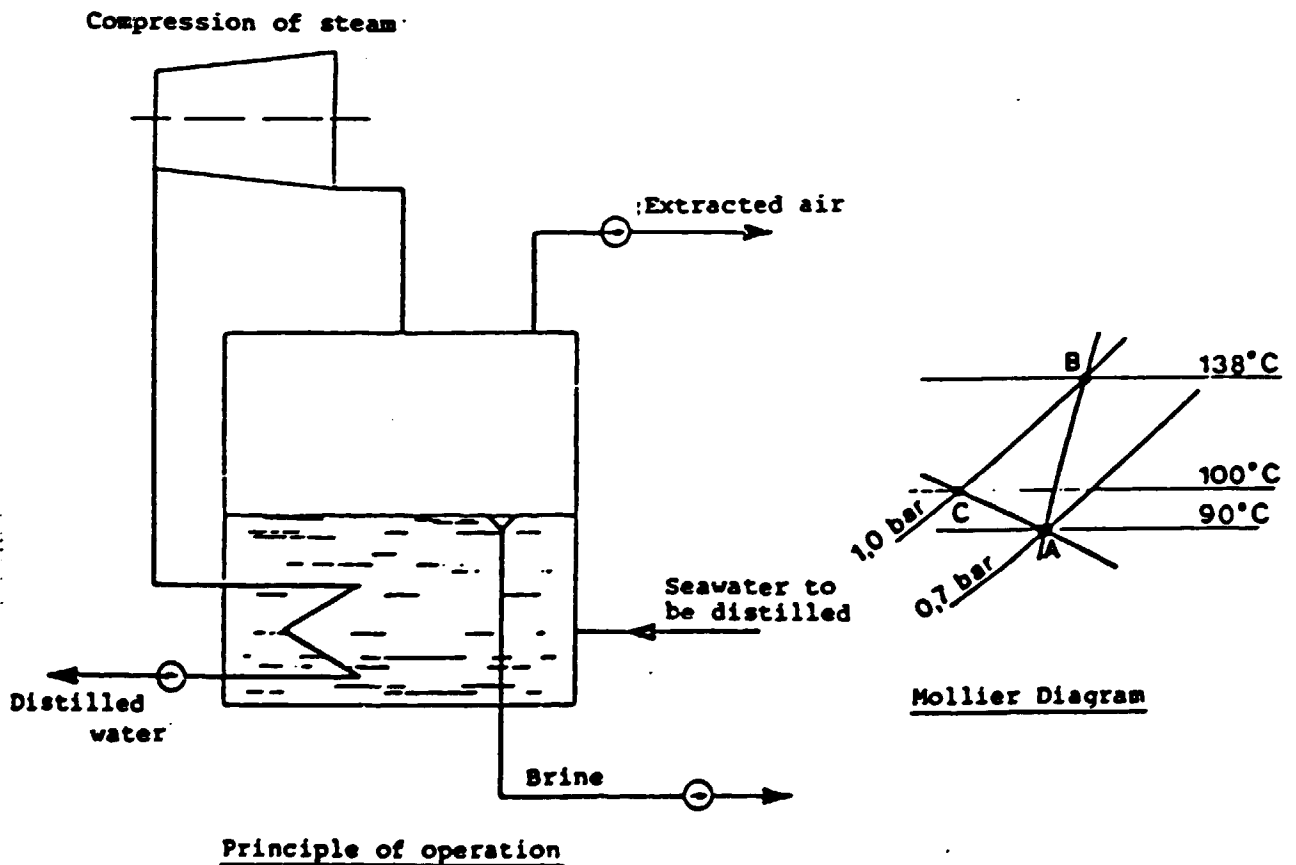
The steam can be compressed by:

. Steam ejectors. Called thermal compression, this method is only used for low capacity facilities due to the poor efficiency of the ejectors.

. Or by axial or centrifugal compressors. This mechanical compression is employed for capacities of several thousand m^3 per day but it is as yet limited by the technological problems inherent in the construction of large compressors.

Nevertheless numerous facilities of this type are in operation throughout the world in ships, military bases, small islands, etc.

FIG. 7 - COMPRESSION OF STEAM



1.2 - Membrane processes

Instead of extracting freshwater from seawater by evaporation, selective membranes may be used for separating the water from the dissolved salts. These methods appear at first to be attractive as they should be able to operate at ambient temperature and do not involve any phase changes. The two membrane methods commercially available are electrodialysis and reverse osmosis. These processes were initially developed primarily for brackish water, which has a lower salinity (i.e. generally 1-10 g/l) than that of seawater. This type of water is very common in North Africa, the Middle East and certain regions of the USA.

1.2.2 - Electrodialysis

Electrodialysis, the oldest membrane process with the first plant dating from the 1960s, eliminates the salts dissolved in the brackish water by ion migration through selective membranes under the action of an electric field.

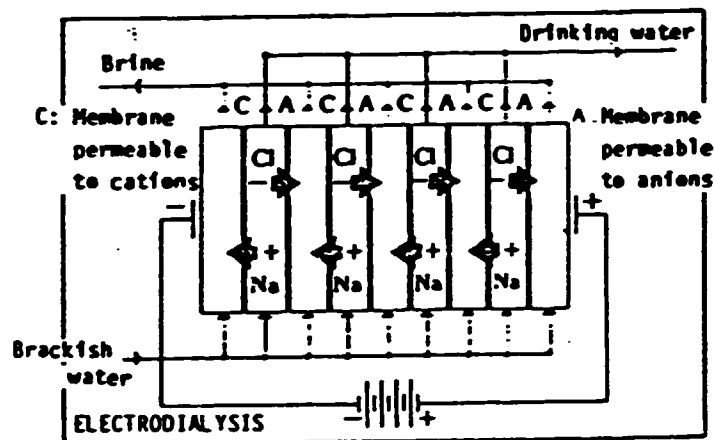


FIG. 8 - Principle of desalination of salty water by electrodialysis

Sulphonic polystyrene ion exchange membranes are used for the cation exchange membranes and quaternary ammonium for the anion exchange membranes. The membranes consist of 0.2-0.8 mm thick sheets and have an operating life of about 5 years.

The Soviet Union has been mainly responsible for the development of this process and operates numerous plants mainly in the dry southern regions. Since 1960 the American company Ionics has installed more than 1000 electrodialysis plants with a total daily yield of approximately 460,000 m³, mainly in the Middle East.

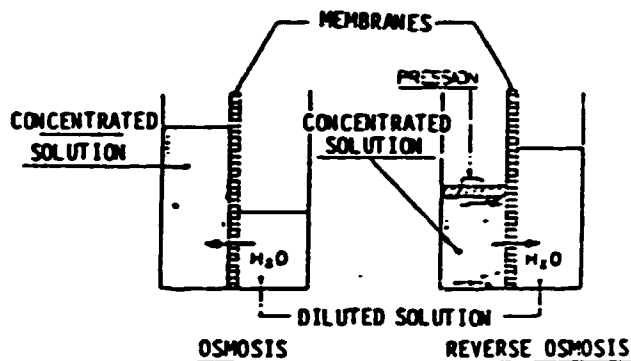
1.2.2 - Reverse Osmosis (FIG. 9)

The principle of osmosis uses a recipient divided into two compartments: one contains pure water and the other salty water. A pressure difference is generated across the membrane and the pure water will then diffuse into the salty water. The resulting difference in level is a measure of the osmotic pressure across the membrane.

If a pressure greater than the osmotic pressure is applied on top of the salty water, the diffusion will occur in the opposite direction and pure water will thus be extracted from the salty water. This is the principle used in reverse osmosis.

The osmotic pressure is proportional to the dissolved salt content, i.e. approx. 0.7 bar per gram/liter of salinity, which means about 25 bar for seawater. To obtain adequate flowrates, the applied pressure must be considerably higher than this theoretical value and for seawater a 60 bar pressure is currently used.

FIG. 9 - PRINCIPLE OF REVERSE OSMOSIS



The key element in this method is the permeable membrane, of which two types are in operational use: cellulose acetate and non-cellulose membranes.

a) Cellulose acetate membranes

The older cellulose acetate based membranes have excellent semi-permeable properties that were revealed by Reid and Breton (University of Florida) in 1959. Several years later at the University of California Loeb and Sourirajan

successfully produced asymmetric membranes with high permeability. Cellulose acetates are derived by acetylation using acetic anhydride and sulphuric acid. Although these membranes have good selectivity and permeability performance, they do feature certain drawbacks:

- Sensitivity to hydrolysis phenomena (the acetate functions are progressively replaced by OH groups), which entails operating at a pH between 5 and 6.

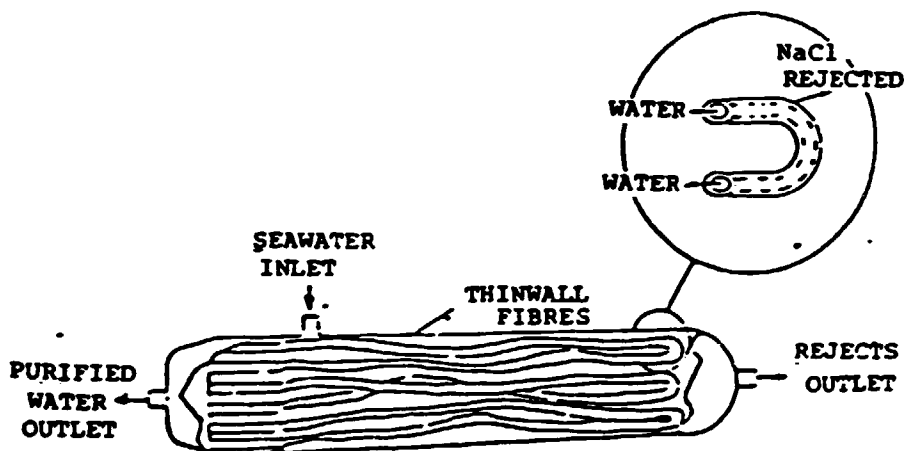
- Sensitivity to compaction, which results in progressive decrease in the flow due to the pressure difference.
 - Liable to deterioration due to bacteria and operation above 30-35 °C.
- This explains the considerable past and current research programs for more resistant materials.

b) Synthetic polymer membranes

The first non-cellulose membranes marketed around 1970 by the American company Dupont de Nemours were made of aromatic polyamide thinwall fibres with a 40 micron ID and a 80 micron OD. The chemical composition means the membranes are very stable and can be employed in areas with pH = 1-11. The membranes are commercially available in modules: PERMASEP B9 for brackish water processing and PERMASEP B10 for seawater desalination (FIG. 10).

Other membranes, such as amide polyether, urea polyether and polybenzimidazolone, are also marketed.

FIG. 10 - THINWALL FIBRE MODULE

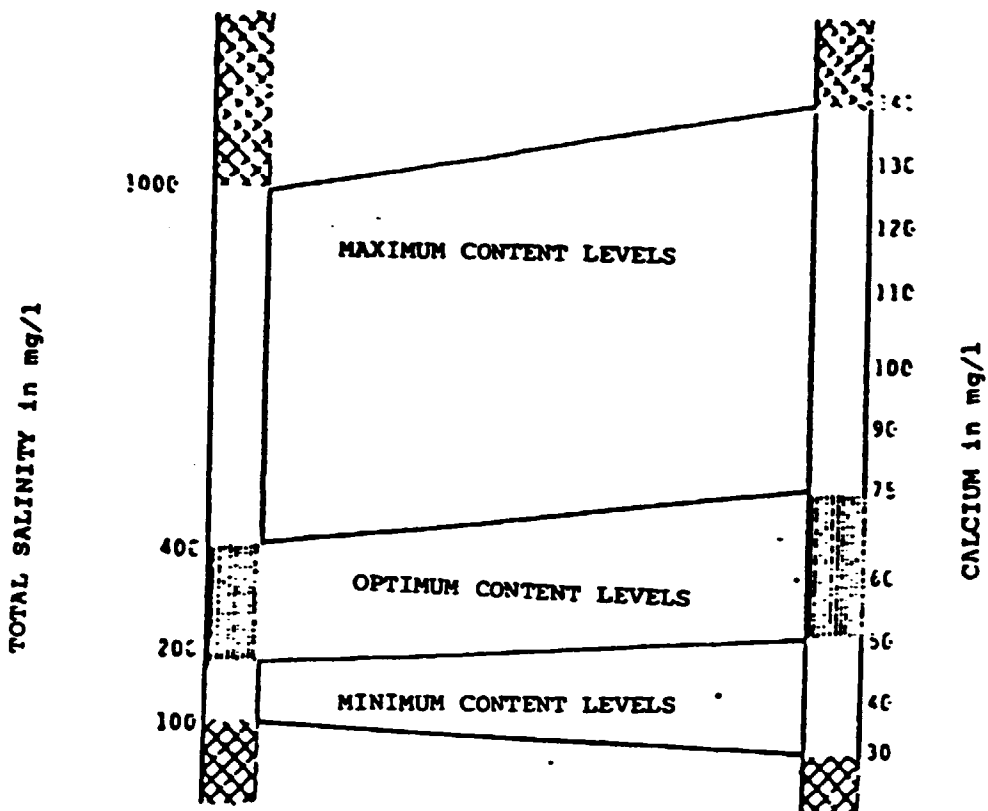


1.3 - Water quality from the various processes

1.3.1 - Water quality from distillation

The demineralized water produced by distillation is extremely pure (10-30 mg/l) and its salinity for domestic consumption is even too low (FIG. 11) and must be increased by adding mineral salts to approximately 300 mg/l.

FIG. 11 - DESIRED SALINITY AND CALCIUM CONTENT FOR DRINKING WATER



Salts can be added by mixing the distilled water with brackish (when available). This procedure:

- . enhances the utility of the brackish water,
- . reduces the desalination costs by increasing production.

1.3.2 - Water quality from membrane processes

. Electrodialysis

With electrodialysis it is difficult technically and economically costly to produce demineralized water with a salinity less than 300-400 mg/l.

This procedure is mainly suitable for domestic purposes.

. Reverse osmosis

With reverse osmosis the resulting water salinity primarily depends on the membrane selectivity. For seawater, membranes with a selectivity of roughly 99% are used and water close to 400 ppm is obtained from 40 g/l seawater. The membrane selectivity for brackish water is around 90%, producing water with a 100-500 mg/l salinity when the brackish water salinity is between 1 and 5 g/l.

2 - DESALINATION ENERGY REQUIREMENTS

2.1 - Minimum desalination energy

Energy is necessary for converting seawater into freshwater: thermal energy for the distillation methods, electrical energy for electro dialysis and solely mechanical energy for reverse osmosis. If these processes operated as reversible processes, each of them would require the same energy for desalination.

For seawater the minimum power requirement is 0.7 kWh/m^3 at a zero conversion ratio where the conversion ratio is given by:

$$\text{Conversion ratio} = \frac{\text{Amount of demineralized water}}{\text{Amount of water input into plant}}$$

FIG.12 shows the variation of the minimum desalination energy requirements with conversion ratio and the salinity of the water being processed.

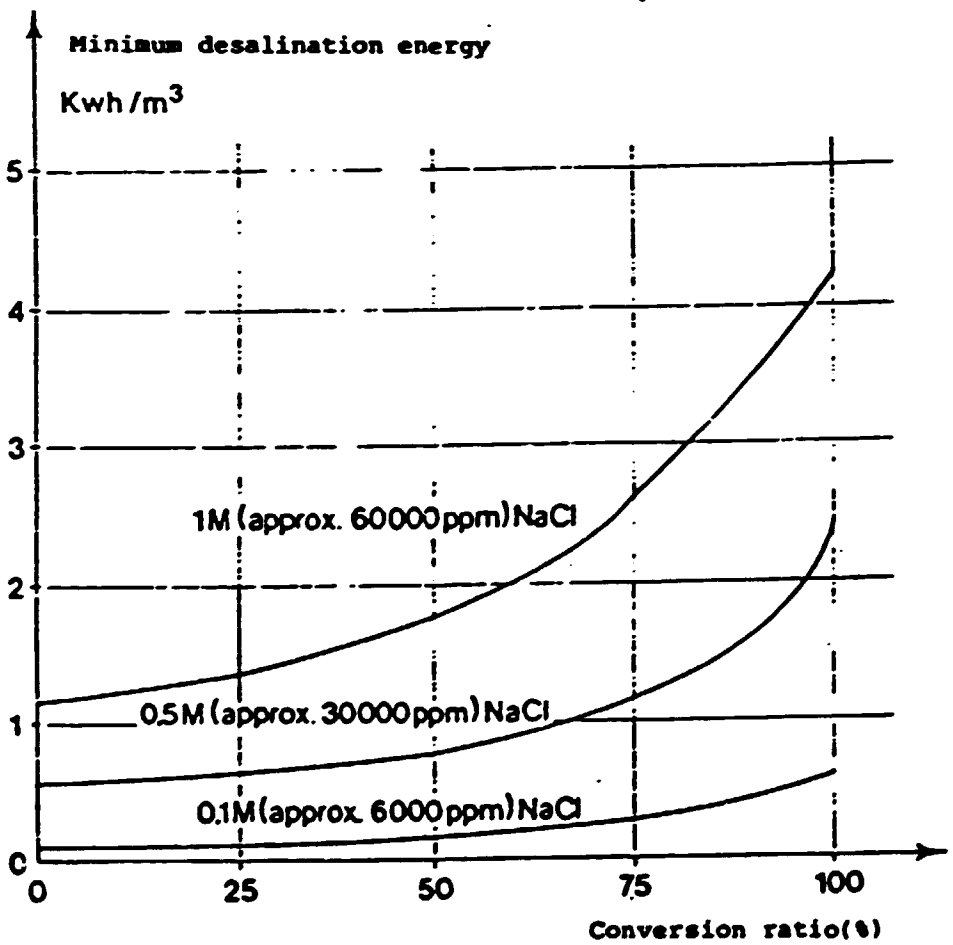


FIG. 12 - MINIMUM ENERGY REQUIRED TO PRODUCE 1 m^3 OF FRESHWATER FROM SALINE WATER ($25 \text{ }^\circ\text{C}$)

2.2 - Energy required in practice

In practice the amount of energy required is much greater than the values given above for two main reasons:

a) To operate a desalination facility in conditions of reversibility would necessitate an infinite exchange surface (heat or matter). Consequently an optimum economic tradeoff must be found between the capital and energy costs, as indicated in FIG. 13.

b) In addition to the energy for the desalination process, energy is also required for the ancillary equipment, i.e. pumps.

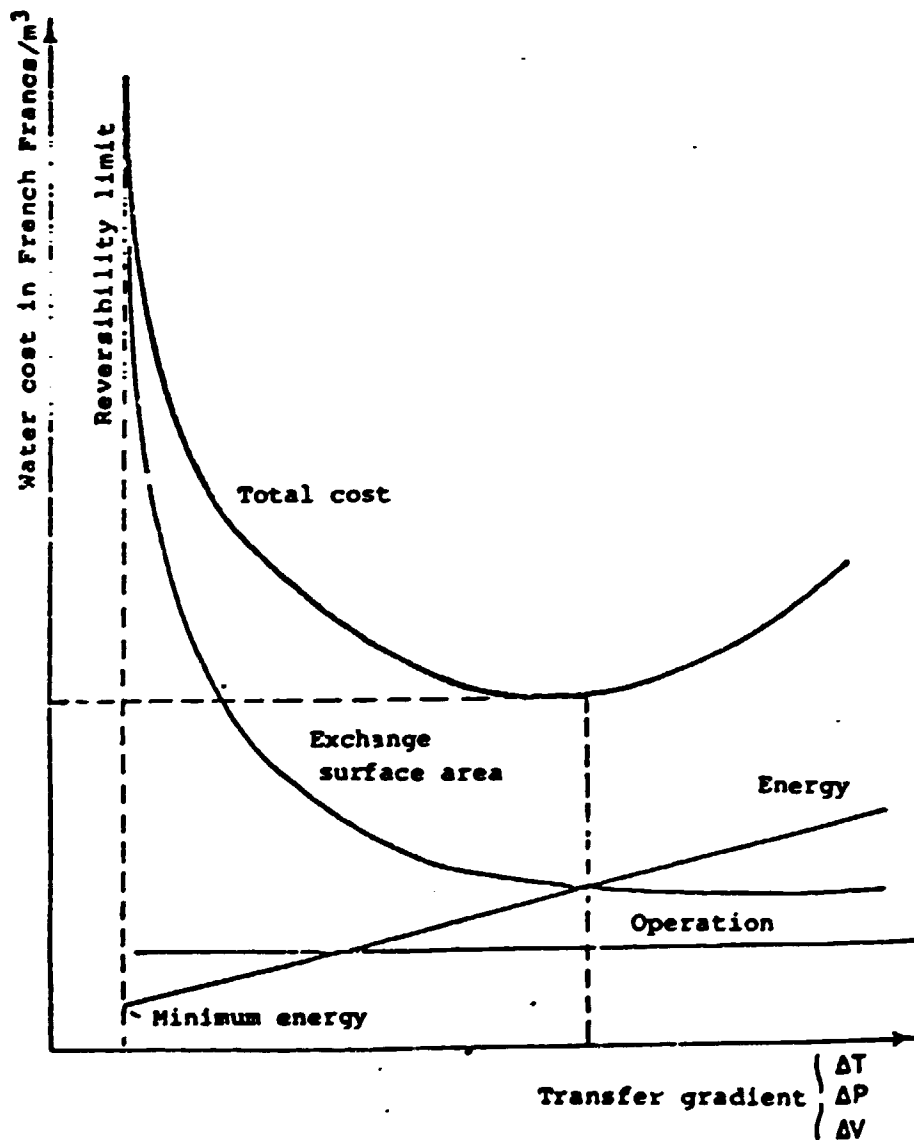


FIG.13 - OPTIMIZATION OF A DESALINATION UNIT

2.3 General case of flash process

A desalination plant based on the flash process has high operating energy requirements that are distributed as follows:

a) mainly for low pressure (2-3 bar) steam used to heat the seawater, i.e. 0.08-0.15 tonnes of steam per m³ of water produced depending on the facility's efficiency (FIG. 14).

$$Q = \frac{550}{R}$$

where Q is the amount of heat required in thermies/m³ and R is the efficiency of the facility.

The efficiency of a distillation unit is normally defined by the ratio R where:

$$R = \frac{\text{Amount of water produced}}{\text{Amount of steam used}}$$

b) Electricity for the plant ancillaries, mainly the pumps of 4-5 kWh per m³ of freshwater produced. In the recirculation flash process the seawater recirculation pump consumes a large part of this energy. For instance, each 22,500 m³/day unit in the Kuwait plant built by Gedes includes a 3600 kW electric pump generator.

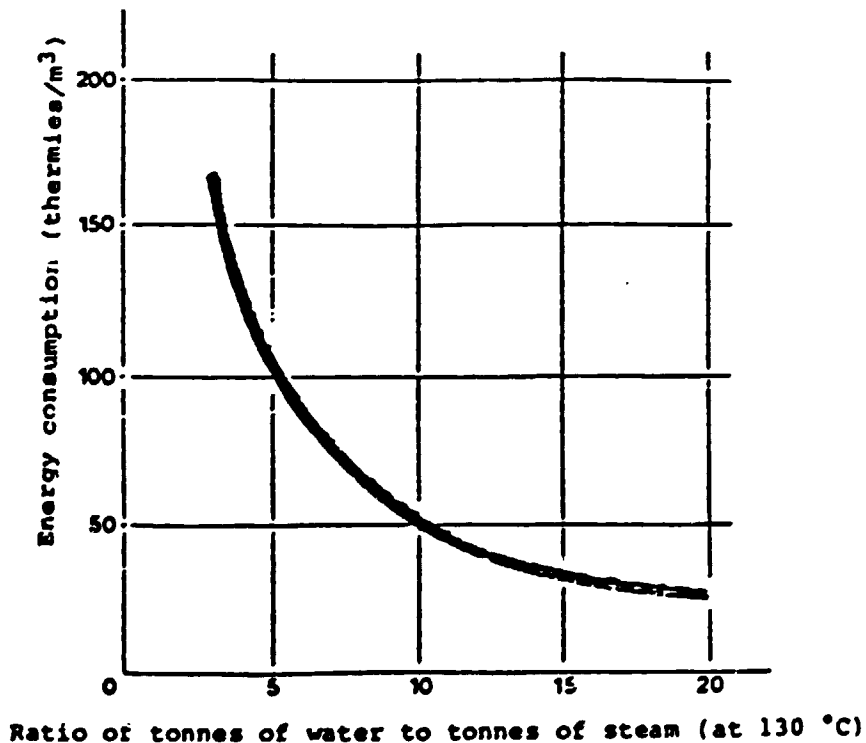


FIG. 14 - DESALINATION BY DISTILLATION:
VARIATION OF ENERGY REQUIRED WITH EFFICIENCY RATIO

In certain cases, turbopumps operating with medium pressure (0.020 tonne/m³) steam can be used.

c) Small amounts of medium pressure steam and steam ejectors are needed for the partial vacuum in the desalination facility (2-3.10⁻³ tonnes/m³).

2.4 - Reverse osmosis

The energy requirements for reverse osmosis depend on the extraction ratio, the operating pressure and the pump efficiency:

$$W = \frac{\Delta P}{36,7 \cdot Y \cdot \eta_p}$$

where W = Energy consumption in kWh/m³
 ΔP = Pressure in bar
 Y = Conversion ratio
 η_p = Pump efficiency

Generally the brine circuit is expanded through a valve with the ensuing losses in energy. However, the expansion of the high pressure fluid can be made through a turbine. Let P' be the module pressure loss and η_{turb} the turbine efficiency, then the energy recovered W_{turb} equals:

$$W_{turb} = \frac{1}{36,7} (P - \Delta P') \eta_{turb} \left(\frac{1}{Y} - 1\right)$$

Hence the actual energy consumption is:

$$W' = W - W_{turb}$$

The decision to use a turbine must be based on a comparison of the cost of the annual payments due to the additional investment and the cost of the energy recovered. The characteristics of a turbine pump, developed by the firm Guinard and recovering about 43% of the incident energy, are given in figure 15.

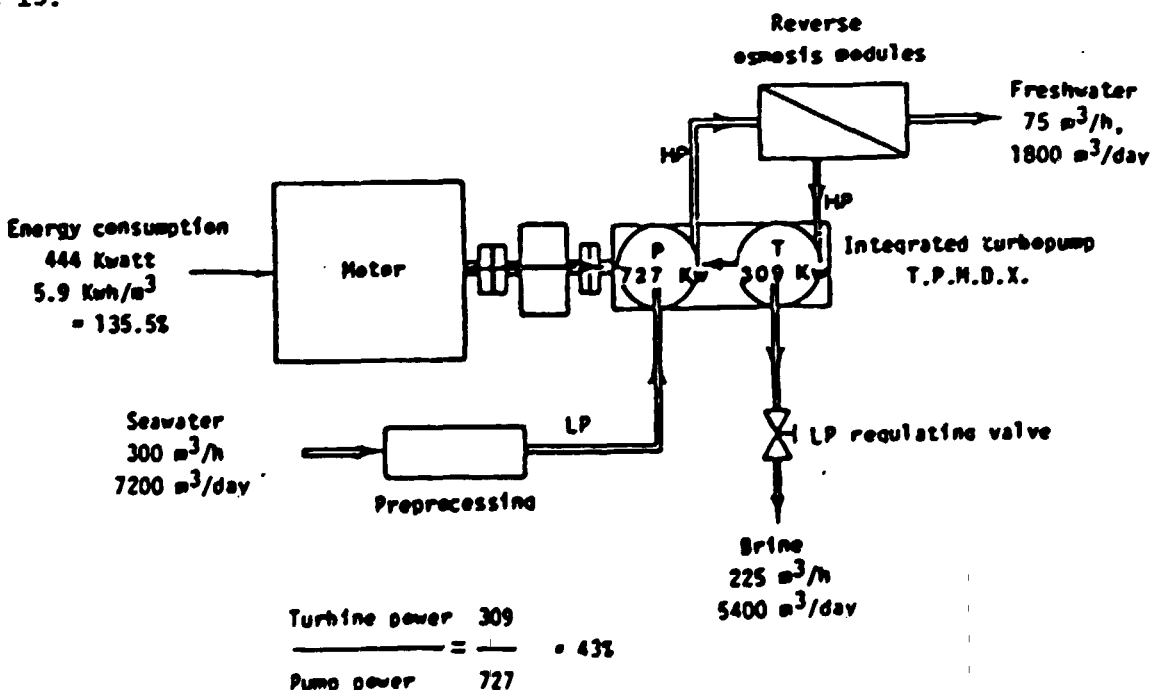


FIG. 15 - ENERGY RECOVERY WITH REVERSE OSMOSIS

2.5 - Self-contained and dual-purpose facilities

The distillation processes using thermal energy (flash, VTE, HTME) employ most of it at a relatively low level as technological factors, especially scaling problems, limit the seawater temperature to 110-120 °C or below. It is thus logical to use degraded heat and connect the distillation to an energy generator (FIG. 16), provided the electricity and water needs are compatible.

The HP steam is initially fed through the turbine to generate electricity. The expanded steam (generally at 2 bar and 120 °C) is then sent to the distillation unit. Due to the price of oil, it is not feasible to build high capacity single effect thermal distillation plants, which burn oil to distill seawater. As far as we know the only high capacity plant (180,000 m³/day) is at Hong Kong and it was scheduled before the energy crisis. Currently desalination plants outputting over 5000 m³/day approx. (1 MGD) must be associated with electric power stations, i.e. conventional (fuel oil, gas, etc.) or nuclear.

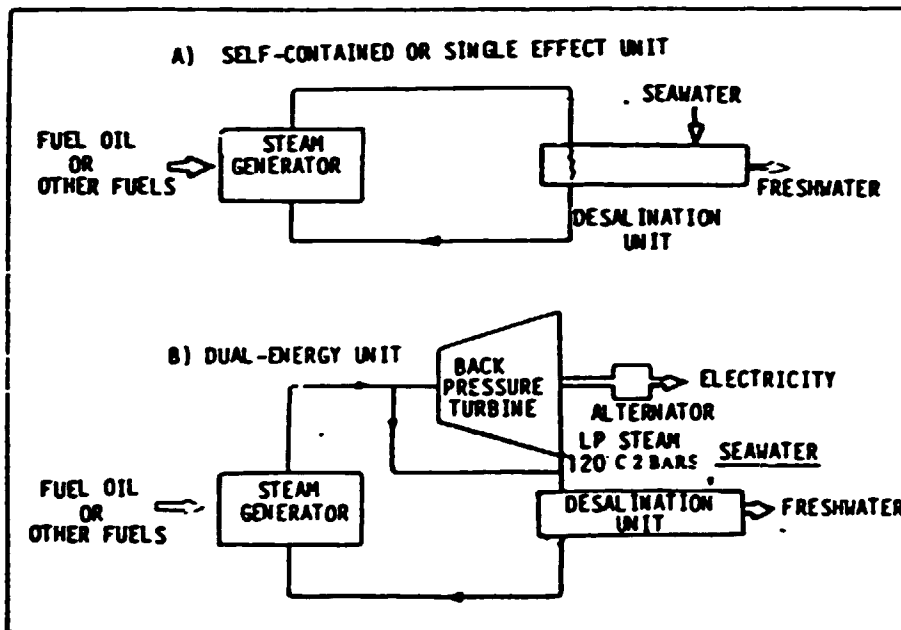


FIG. 16 SELF-CONTAINED AND DOUBLE EFFECT FACILITIES

2.6 - Order of magnitude of energy consumption for various desalination processes

The energy consumed by the different desalination processes is given as an order of magnitude in Table 11.

Two values of efficiency are shown corresponding to the different capital costs.

Since some processes need low level thermal energy and others electric power, we have taken fuel oil as the primary energy for facilitating the comparison and made the following assumptions:

- fuel oil at 10,000 Kcal/kg
- steam generator efficiency 85%
- electric genertor efficiency 90%

This yields an overall efficiency of 2.5 thermies/kWh.

DESALINATION PROCESS		Required energy lh/m ³ +kWh/m ³	Amount fuel kg/m ³	
			Sing. purp.	Doub. Purp.
DISTILL. PROC.	<u>MULTIFLASH Ratio B</u>	<u>70 + 3</u>	<u>8,45</u>	<u>3,5</u>
	MULTIFLASH Ratio 14	40 + 5	5,65	2,8
	<u>MULTIP. EFFECTS (7)</u>	<u>90 + 2</u>	<u>10,4</u>	<u>4</u>
	MULTIP. EFFECTS (12)	60 + 3	6,25	2,7
	<u>Steam compr(1) Δt#5°C</u>	<u>0 + 16</u>	<u>4</u>	<u>4</u>
	Steam compr(1) Δt#3°C	0 + 12	4	4
MEMBRANE PROC.	<u>RO seawater, no recov. (60 bar)</u>	<u>0 + 12</u>	<u>3</u>	<u>3</u>
	RO seawater + recov. (60 bar)	0 + 8	2	2
	<u>RO brack. 2.5g/l water (40 bar)</u>	<u>0 + 3</u>	<u>0,75</u>	<u>0,75</u>
	ED seawater 1.2 volt/cell	0 + 30	7,50	7,50
	<u>ED brack.2.5g/l water 1.2 volt/cell</u>	<u>0 + 3</u>	<u>0,75</u>	<u>0,75</u>

(1) Single effect

RO Reverse osmosis

ED Electrodialysis

Table II - COMPARISON OF ENERGY CONSUMPTION FOR DIFFERENT DESALINATION PROCESSE ASSUMING PRIMARY ENERGY SOURCE IS FUEL OIL

Underlined values represent the state of the art.

3 - TECHNICAL PROBLEMS

The main problems in desalinating seawater and brackish water are scaling, corrosion and fouling of exchange surfaces.

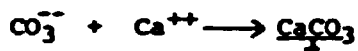
3.1 - Scaling

Scaling is a deposit of mineral salts that tend to form on exchange surface. Because of the ions in saline water (calcium, magnesium, bicarbonate, sulphate) the deposits mainly consist of calcium carbonate (CaCO_3), magnesium hydroxide (Mg(OH)_2) and calcium sulphate (CaSO_4). Scaling is caused by a complex array of factors:

- Average concentrations too high. A conversion ratio of 90% thus implies a concentration factor of 10 for the saline water.

- Local over-concentrations near the transfer surfaces due to poor hydrodynamic flow conditions (polarization phenomenon).

- Operating temperature above the solubility limit of the salts. As a result salts may be deposited in distillation units above 60 °C according to the reactions:



Scale buildup normally results in a decreased unit output or higher energy consumption. To illustrate the problem, the production capacity of a distillation unit can, in the worst case, drop by over 40% in a 24 hour period.

Several methods for fighting against scaling are available:

- Injection of a few ppm of scale preventing products in the water being treated. For example the polyphosphates used in distillation adsorb on the CaCO_3 crystal nuclei formed and prevent them from growing by physical action alone.

- decomposition of the bicarbonates by a strong acid (mostly sulphuric acid) with formation of carbon dioxide.

- elimination of scaling elements (calcium, magnesium) upstream of the desalination unit by ion exchange or prior precipitation.

3.2 Corrosion

The significant corrosive properties of seawater at high temperatures are caused by several factors:

- (its chemical composition and especially the large number of chloride ions,

- high conductivity, promoting subsequent galvanic action,

- corrosion resulting from dissolved oxygen,

- presence of bacteria on various marine organisms and of H_2S in some pollution.

Noble materials such as aluminium bronze, stainless steels and cupro-nickels must be used in all cases, the choice of material depending on the temperature, feed speeds, preprocessing adopted (i.e. acid or scale preventers) and their cost.

3.3 - Fouling

Natural water (sea or brackish water) normally contains suspended organic matter that tends to settle on and foul up exchange surfaces. This increases the transfer resistance and reduces the production capacity of the facility. This problem is especially important in the reverse osmosis, which can as a first approximation be assumed to be a process filtering down to several Angstroms. This is why reverse osmosis plants require substantial preprocessing of the water, i.e.:

- coagulation and flocculation
- settling
- prefiltering on sand bed or diatom filters
- fine filtering through cartridges.

4 - COST OF DESALINATED WATER

We have estimated the costs of desalinated water for plants producing 100, 1000, 10000, and 100000 m³ per day. For the distillation plants standard seawater (35 g/l) was taken as the water to be desalinated and for the membrane type plants brackish water with a 2.5 g/l salinity was assumed.

4.1 - Capital costs

The specific capital costs in French Francs per m³/day production can be broken down into two parts:

- a) cost of the factory alone
- b) owner's expenses.

a) Cost of the factory alone

This charge includes the cost of the desalination plant constructed on a serviced site with steam and electricity on hand, except for small facilities when the steam generator is included.

Although the cost is a function of the materials selected and level of automation, it is above all strongly dependent on the efficiency chosen for the plant. This means that though an 8-effect unit will be twice as expensive as a 4-effect unit, it will only consume half the energy. It is thus clear that the efficiency selected must be a tradeoff between the cost of energy and its forecasted variation with time, when this can be estimated.

b) Owner's expenses

These investments include the following:

- . initial investigations and engineer consulting fees,
- . possible land purchasing and site preparation, i.e. civil engineering works, access roads, fencing, etc.,
- . seawater supply, i.e. pumping, large-size filtering, chloriding. It should not be forgotten that the flash process requires approximately 10 m³ of seawater to be pumped to produce 1 m³ of freshwater.

- . disposal of the brine rejects (the area must be located sufficiently far away from the seawater tapping point,
- . the piping and freshwater storage,
- . detail part and tool stores and a set of spares,
- . the startup of the plant and personnel training.

It is obvious that this part of the investment depends on the individual case. It can be very low for a plant located on an existing industrial site, as with the 22,500 m³/day plant constructed by IHI at Shuaiba (Koweit) in 1975 or with the 1500 m³/h unit built by SIT at the Porto-Torres petro-chemical complex. On a site without any infrastructure, these costs can, however, be high.

These owner costs have been estimated as overall sums of 5000, 3200, 2000 and 1250 French Francs per m³/day production for production capacities of 100, 1000, 10000 and 100000 m³/day respectively.

As the membrane processes are smaller, we have used lower estimates.

4.2 - Financial charges

The financial charges, i.e. repayment and return on capital invested, were calculated for determining the cost price per m³ of water produced with the following assumptions:

PARAMETER	DISTILLATION	MEMBRANE
Depreciation period	20 years (1)	15 years
Interest rate	7%	7%
Annual installments	9.43%	10.9%
Annual workload	300/365	300/365

We have not included assurance premiums, land rates and interim expenses.

4.3 - Cost of energy

In the last few years the cost of energy and especially the cost of oil has varied very significantly (FIG. 17).

However in today's context, energy is still relatively cheap in the Middle East, the home of most of the desalination plants. The majority of these countries possess large amounts of natural gas that cannot be exported due to the lack of liquefaction plants.

(1) A depreciation period of 15 years has been assumed for the small steam compressor units.

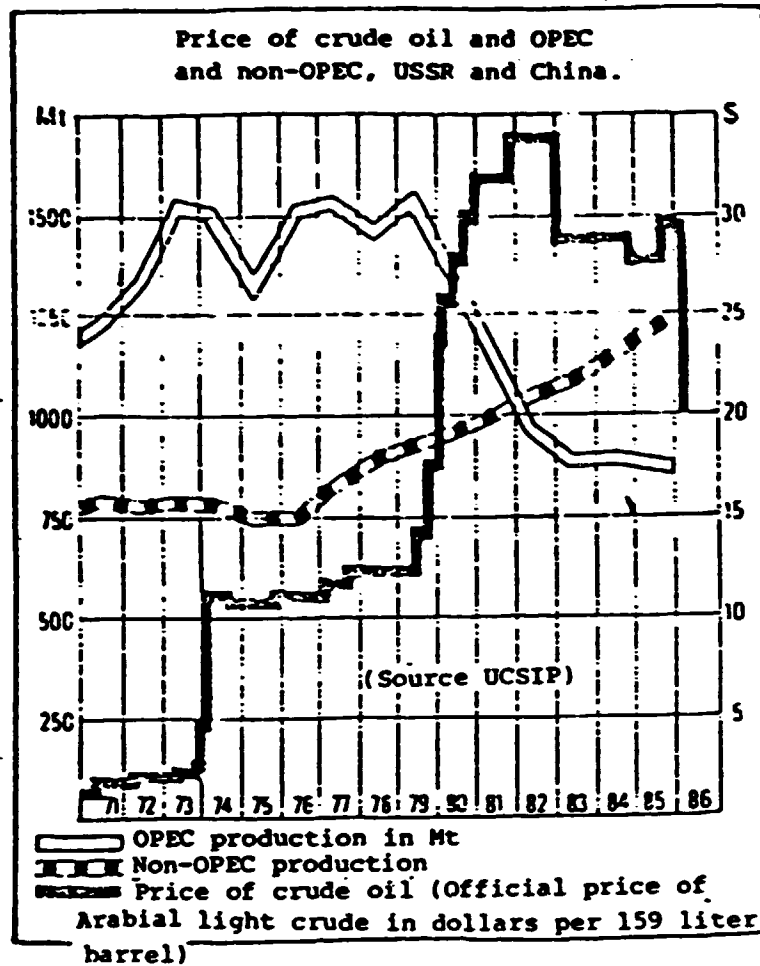


FIG. 17 - VARIATION OF OIL PRICES DURING THE LAST FEW YEARS

Based on the above, we have used the following values:

LP steam	15 French Francs/tonne for small units 10 French Francs/tonne for large units
Electric power	0.20 French Francs/kWh for small units 0.15 French Francs/kWh for large units

4.4 - Control - Operation - Maintenance

This item is one of the most difficult to evaluate as it can vary substantially depending on the reliability, of the plant, its automation level and the competence of the personnel.

For example, the 36,000 m³/day plant at Porto-Torres needs only two persons to run it: all the data (temperatures, pressures, steam available) is fed to a computer which controls the plant process. However, some 3000 m³/day plants require a staff of over 20.

For the cost estimates of desalinated water, we have based the annual process control and maintenance costs on a percentage of the investment in a similar manner to the financial charges:

Capacity m ³ /day	100	1000	10,000	100,000
Annual payment % investment	10%	8%	6%	4%

The cost of replacing membranes in the membrane units has been incorporated in the overall process control and maintenance costs. In a well designed and correctly run plant with suitable preprocessing, the service life of electro dialysis or reverse osmosis membranes is between 3 and 5 years.

4.5 - Order of magnitude for desalinated water costs

Assuming relative favourable economic conditions, the cost price per m³ of desalinated water is at the best 5 F.F for seawater and 1.30 F.F for brackish water (Tables 3 and 4 and Figure 18).

It should be stressed that the salinity of water from distillation is very low (10-25 ppm) and, if drinking water is required, the demineralized water produced by distillation can be mixed with brackish water. This results in a cost reduction that is not insignificant.

The desalination costs from an investigation made by USAID in 1980 are given in figures 19 and 20 for comparison.

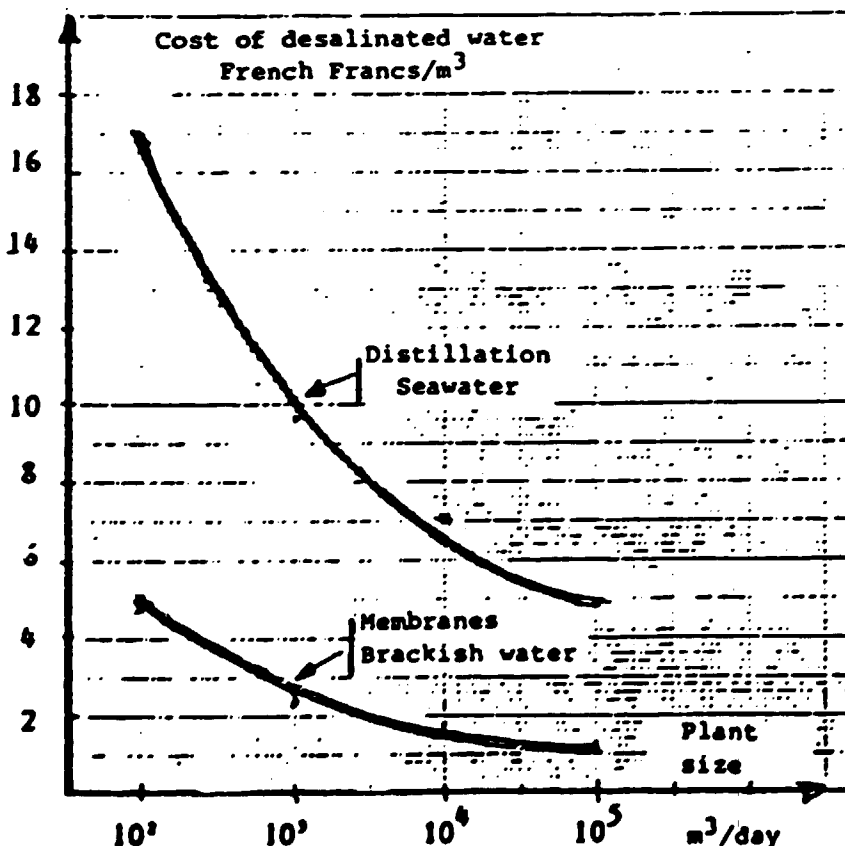


FIG. 18 - VARIATION OF DESALINATION COSTS WITH PLANT SIZE

Production capacity (m ³ /day)		100	1000	10 000	100 000
General characteristics	Single - or double - units	Single purpose		Double purpose	
	Type of process	STEAM COMPRESSION		MULTI-FLASH	
	Energy source	ELECTRICITY		HEAVY GASOIL	
Specific investment FF per m ³ /day	Price with EVAPORATOR INSTALLED Owner's expenses TOTAL	13 000 5 000 <u>18 000</u>	9 000 3 200 <u>12 200</u>	8 000 2 000 <u>10 000</u>	5 500 1 250 <u>6 750</u>
Thermodynamic output in tons water/tons steam Thermal energy required in tons steam/m ³ Price of LP steam in FF/ton Electric energy required in kwh/m ³ Price of electric energy in FF/kwh Depreciation period Interest rates Annual payments of financial charges as % Annual payments of operating costs as %		-	8	8	8
		-	0,125	0,125	0,125
		-	15	10	10
		20	4	4	4
		0,20	0,15	0,15	0,15
		15	20	20	20
				7%	
			10,9		9,43
price of installed unit in FF/m ³	Financial charges	6,54	3,83	3,14	2,12
	Thermal energy	-	1,87	1,25	1,25
	Electric energy	4	0,60	0,60	0,60
	Control and maintenance	6	3,25	2,00	0,90
	TOTAL ROUNDED OFF	<u>16,54</u> 16,6	<u>9,55</u> 9,6	<u>6,99</u> 7,0	<u>4,87</u> 4,9

Production capacity (m ³ /day)		REVERSE OSMOSIS				ELECTRODIALYSIS			
		10 ²	10 ³	10 ⁴	10 ⁵	10 ²	10 ³	10 ⁴	10 ⁵
Specific investment FF/d	Desalination unit alone	4 000	2 000	1 300	1 000	4 000	2 000	1 300	1 000
	Preprocessing	1 100	800	600	400	800	500	300	200
	Owner's expenses	<u>1 200</u>	<u>600</u>	<u>500</u>	<u>400</u>	<u>1 200</u>	<u>600</u>	<u>500</u>	<u>400</u>
	TOTAL	6 300	3 400	2 400	1 800	6 000	3 100	2 100	1 600
Options	Electric power consumption kWh/m ³	← 3 →				← 3 →			
	Price of electric power FF/kWh	0,20	← 0,20 →			← 0,15 →			
	Membrane service life	← 3 to 5 years →				← 3 to 5 years →			
	Depreciation period	← 15 years →				← 15 years →			
	Interest rates	← 7% →				← 7% →			
	Annual payment of financial charges	← 10,9% →				← 10,9% →			
	Annual operating payment as %	10	8	6	4	10	8	6	4
price water exclu- of tax	Financial charges	2,29	1,24	0,87	0,65	2,18	1,13	0,76	0,58
	Electric energy	0,60	0,45	0,45	0,45	0,60	0,45	0,45	0,45
	Control and maintenance	<u>2,10</u>	<u>0,91</u>	<u>0,48</u>	<u>0,24</u>	<u>2,00</u>	<u>0,83</u>	<u>0,42</u>	<u>0,21</u>
	TOTAL	4,99	2,60	1,80	1,34	4,78	2,41	1,63	1,24
	ROUNDED OFF	5	2,6	1,8	1,3	4,8	2,4	1,6	1,2

TABLE 4 REVERSE OSMOSIS AND ELECTRODIALYSIS DESALINATION COSTS
FOR 2.5 g/l BRACKISH WATER

WARNING

1. Caution should be exercised when using these cost data.
2. These costs are computed for basic desalination facilities in the USA. These costs include no storage capacity and allow for only fundamental feedwater development and brine disposal. If storage capacity is needed and/or more complex feedwater or brine facilities are required, overall project costs can significantly increase. This is especially true with brackish water facilities. Construction in locations outside the USA can also add to the overall cost. Actual costs of up to 300% (or more) of those shown on this figure (especially at lower capacities) would not be unusual for projects in many developing areas.

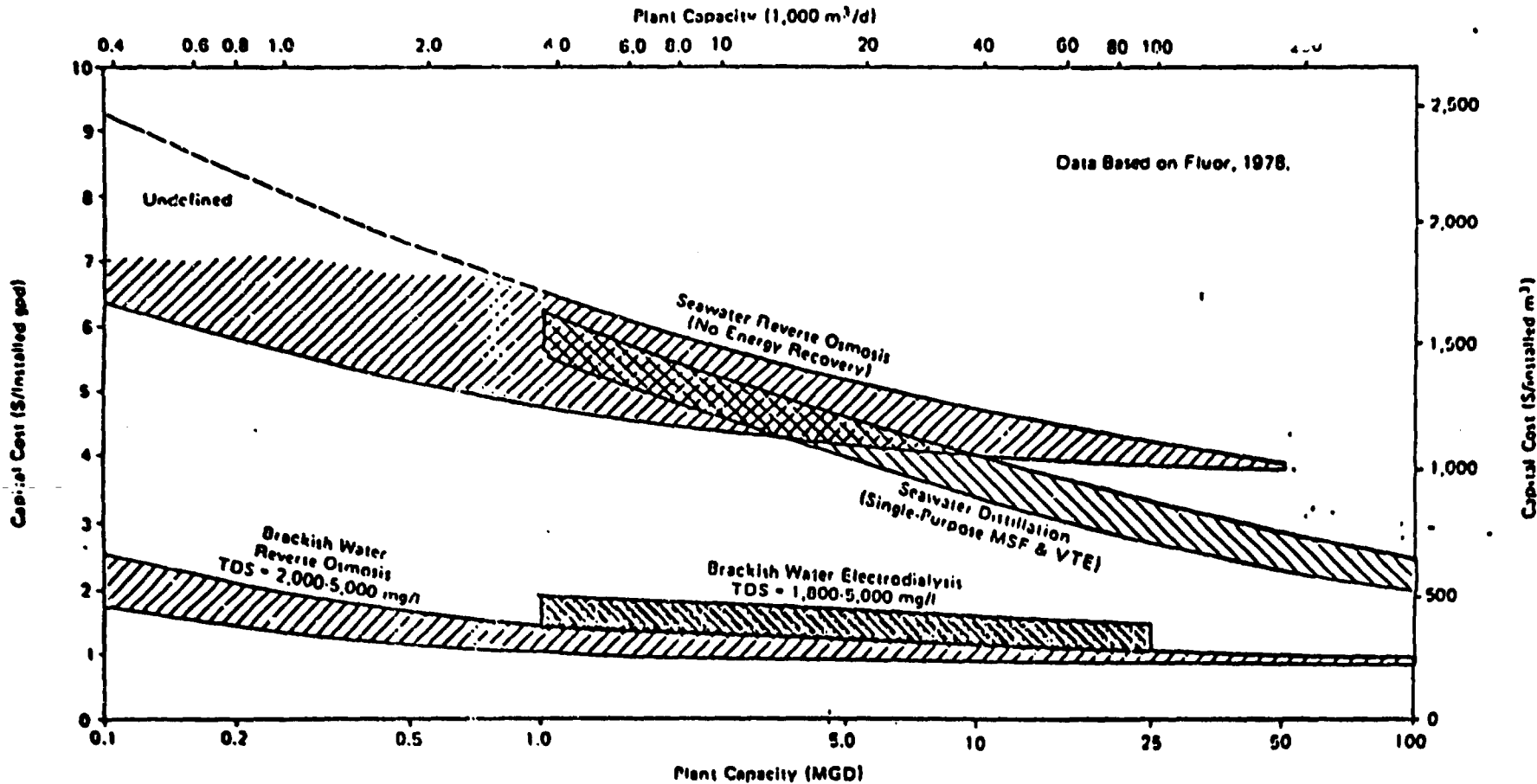


FIGURE 19 : COMPARISON OF CAPITAL COSTS FOR VARIOUS DESALINATION PROCESSES
SOURCE : USAID DESALINATION MANUAL, AUGUST 1968

WARNING

1. Caution should be exercised when using these cost data.
2. These costs are computed for basic desalination facilities in the USA. These costs include no storage capacity and allow for only fundamental feedwater development and brine disposal. If storage capacity is added and/or more complex feedwater or brine facilities are required, overall project costs can significantly increase. This is especially true with brackish water facilities. Construction in locations outside the USA can also add to the overall cost. Actual costs of up to 300% (or more) of those shown on this figure (especially at lower capacities) would not be unusual for projects in many developing areas.

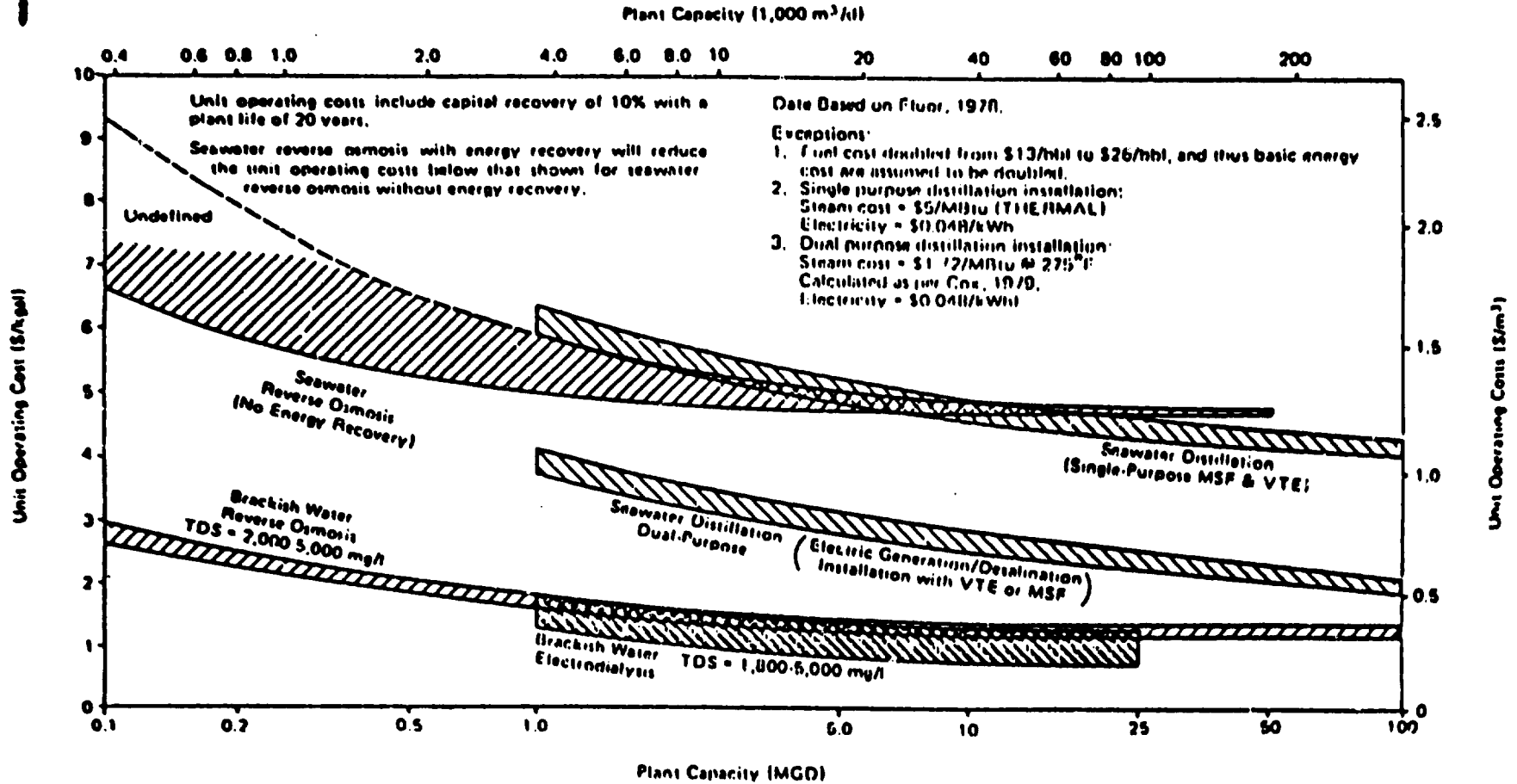


FIGURE 20 : COMPARISON OF DESALINATION COSTS FOR VARIOUS DESALINATION PROCESSES - SOURCE : USAID DESALINATION MANUAL, AUGUST 1980

5 - UNCONVENTIONAL DESALINATION PROCESSES

5.1 - Solar desalination

After the 1973 oil crisis, the so called soft energies and in particular solar energy came into fashion; however, solar desalination by distillation was practised in the distant past (Figure 21).

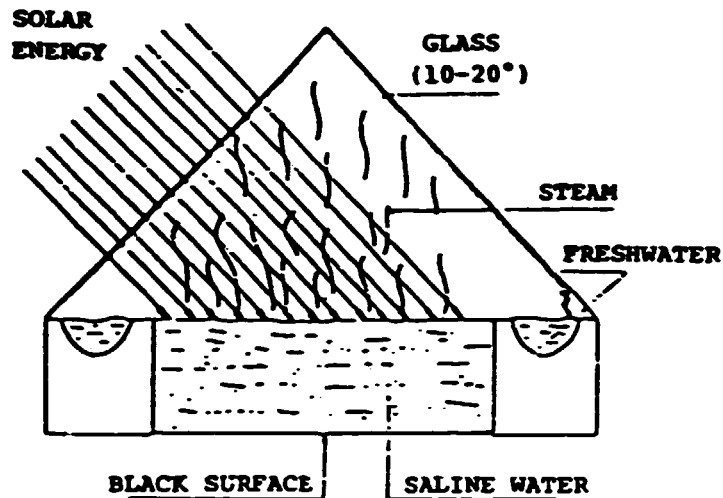


FIG. 21 - PRINCIPLE OF GREENHOUSE DISTILLER

In 1870 an English engineer named Wilson, manager of a mine at Los Salinas in Chile, was faced with the problem of watering 4000 mules that transported nitrate minerals in convoys. As the only water available had a salinity of 140 g/l, i.e. roughly 4 times that of seawater, he decided to build a 4460 m² wooden solar distiller for supplying 20 m³/day approx. of freshwater. The conditions were, it is true, especially ideal in terms of the latitude of the location, its altitude of 1400 m and the pure air. The plant remained in production for over 40 years until 1908.

The capacity of this extremely simple process are, however, very limited as the yield cannot be over 4-5 liters of freshwater per day and per m² of bed. This means that the greenhouse surface area necessary mounts up very quickly.

Another technique is to use renewable energies associated with conventional and highly efficient processes. Two inherent characteristics of renewable energies must, however, be allowed for, i.e. their high cost and discontinuity.

Several demonstration projects have been undertaken in recent years:

- The Python project involving multiple effect distillation using flat solar panels,
- Reverse osmosis units powered by wind generators or photoelectric cells,
- Experimental desalination station using renewable energies at Borg-Cedria in Tunisia.

5.2 - Freezing

Although industrial-scale desalination by freezing is not yet commercially available, research work on the process is being actively pursued in both the laboratory and pilot stations.

Freezing and distillation are in a certain way similar desalination processes in that the liquid saline phase is transformed into another salt-free phase (gas or solid). Reversing the phase change will produce desalinated water.

The freezing process attracts attention because of the low latent heat of freezing compared to that of steam, i.e.:

- . freezing = 80 cal/g at 0 °C
- . steam = 540 cal/g at 100 °C

As a result a single effect freezing operation forming pure ice crystals consumes an amount of energy comparable to the multiple effect distillation.

In fact, it is a mistake to compare the freezing and distillation process energy consumptions since the 540 cal/g required for converting the water into steam are recovered (except the losses) during condensation due to the latent heat released, in the same way that the kilogram calories necessary for freezing the water are recycled.

Furthermore, the heat requirements for evaporation (low energy calories) generally cost less than the cooling necessary for freezing (mechanical energy). When liquefied natural gas is available, this is especially advantageous as the gas gives out kilogram calories as it vaporizes.

5.3 - Towing icebergs?

The idea of towing icebergs from the polar regions to far away countries for use as a source of freshwater is creating widespread interest today. As far back as 1890 and 1900 small icebergs were towed by ship all the way from Laguna San Rafael in Chile to Valpariso or even Callao in Peru, a distance of over 3900 kilometers. Another example is when San Francisco was supplied with ice - in the winter of 1953/54 the usual lake supply in Alaska gave out and the ship had to load ice from the Buid Glacier, north of Petersburg in Pennsylvania.

In charge of the desalination program for Saudi Arabia until 1977, Prince Mohamed Al Faisal recently took this idea up again and asked for a study to be made by a French company in collaboration with the well known explorer Paul Emile Victor for towing a 100 million ton iceberg from the South Pole to Djeddah in Saudi Arabia. This enormous block of ice would be towed by four tugs and covered by a "skirt" made of synthetic material for insulation based on its melting down. Between 6 and 12 months would be necessary to cover the distance of more than 7000 km. This study estimates the cost of a cubic meter of freshwater, after "cutting up" on arrival, to be 2.50 FF or less than the desalination cost by the flash distillation. Notwithstanding, there appear to be many unresolved technical problems such as:

- The crumbling properties of icebergs,
- The shallowness of the Red Sea,
- The distribution of water on arrival.

6 - CONCLUSIONS

We have attempted in this review to give a technical and economical overview of the various desalination processes.

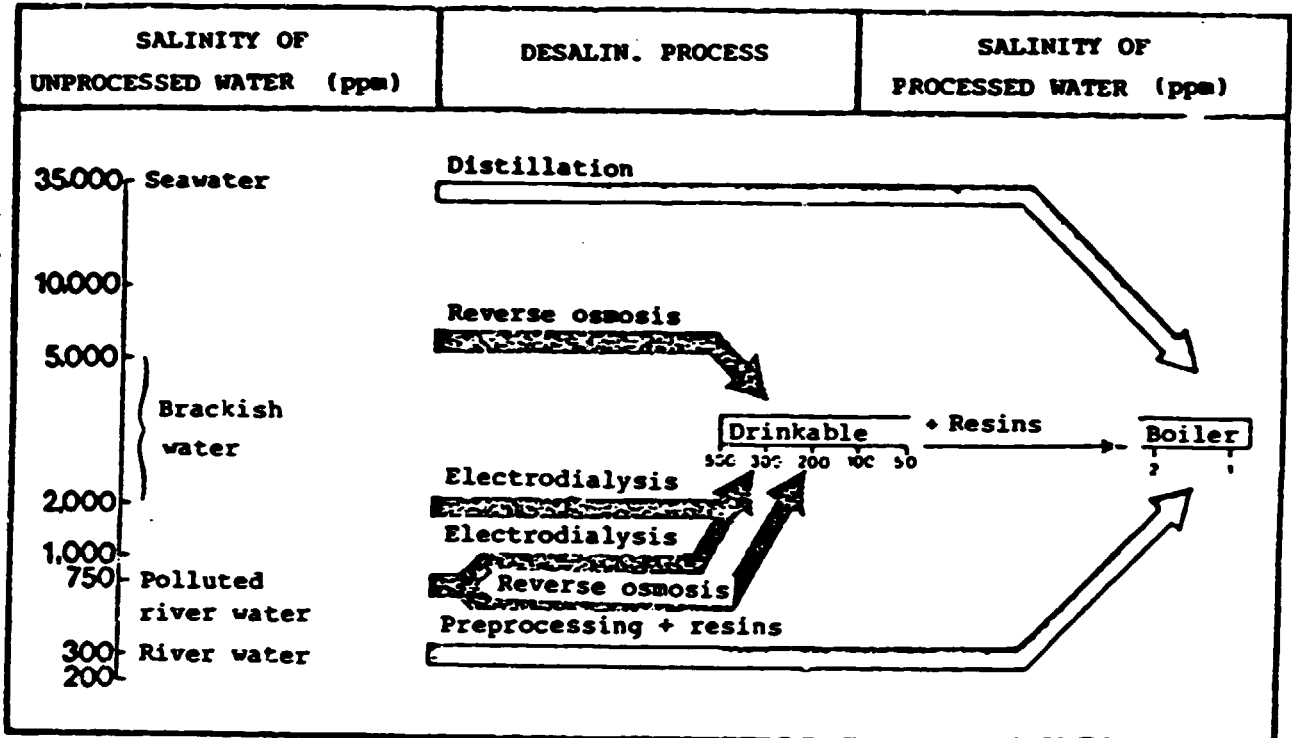


FIG.22 - Choosing a desalination process as a function of process water salinity and processed water salinity

1) For brackish water, the membrane processes offer today the best economical advantages.

The very simple reverse osmosis process has won many markets but it does have several drawbacks:

- the need to chemically flocculate and then fine filter surface brackish water and some borehole water in order to prevent fouling the modules.
- random variations in membrane life.
- module design that mostly does not allow for cleaning, other than chemical procedures, of accidental fouling caused by micro-organisms, suspended matter or scaling.

Electrodialysis is as a rule the best process for low salinity brackish water as it does not feature any of the drawbacks of reverse osmosis. The preprocessing is restricted to simple filtering, water up to 50 °C can be processed with the ensuing savings in energy consumption and its very simple construction makes disassembly and cleaning easy if fouling occurs.

A disadvantage, however, is that its energy consumption is virtually proportional to the salinity of the water being processed.

2) For seawater there are two possibilities:

. Small capacity units producing not more than 1000 m³/day:

Two processes are in competition: distillation (compression of steam, multiple effect) and reverse osmosis. The first process has the advantage that it has been tested more than the second, whereas the second (reverse osmosis) has a lower energy consumption but is penalized by the need for physical/chemical preprocessing.

. Large capacity units producing 5000 m³/day or more:

In this case the distillation processes - the flash type today but undoubtedly the multiple effect units in a few years time. We believe that these processes, which can run on degraded heat (LP steam) from an electric power station (dual purpose plants) are the most promising.